Modelling and optimisation of future energy systems using spatial and temporal methods

Dissertation
for the degree of a Doctor of natural science

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Summary

The energy system needs to undergo major transformations before the system will fulfill major sustainability criteria. Modelling of the system is necessary to understand most of these changes.
The challenge of modelling energy systems can be tackled using many different approaches and methodologies. The choice of approach is normally dependent on the intended aims of the investigation – be these an emphasis on economic or ecological aspects, on the short or long term, on local, regional or global systems, and so on.

This thesis sets out a modelling approach that is particularly suited to systems with significant geographical and temporal dependency, for instance, systems with numerous renewable energy supply technologies.
This new approach is implemented in the software tool TASES (Time And Space resolved Energy Simulation). At the centre of TASES is a flexible data structure. This data structure is implemented as a cross-referenced two dimensional database, where one dimension captures the geographical description of the system while the other one contains the time related dependencies. Extra effort was directed toward the design of this data structure because the details of the mapping will determine which modelling methodologies will later be feasible and which will not.
TASES contains a simulation technique that calculates all respective energy flows within a given scenario. This calculation is based on a heuristic that captures the operational behaviour of the technical processes present in the scenario.
Alongside this simulation functionality are two optimisation techniques that can be used to determine, subject to predefined limitations, beneficial structural changes within a scenario. The first optimisation technique involves the formulation of this problem in linear terms, so that fast well-established linear optimisation routines can be used. More specifically, TASES generates a linear equation matrix describing the complete scenario for submission to a third-party solver.
The second more novel optimisation technique was developed using rules and procedures based on evolutionary algorithms. This technique relies on a more or less complete decoupling of intrinsic complexity of the system from the task of obtaining a global optimal solution. The optimisation process itself uses an analogue of

biological evolution to establish an improving series of approximate solutions. The technique requires customised procedures to mutate and select better performing potential solutions. The most notable advantage of evolutionary optimisation, vis-à-vis linear optimisation, is the flexibility it provides model users by no longer requiring that the underlying problem formulation be linear.
The above methodologies can determine the state of an energy system but not its intrinsic dynamics. These dynamics can be captured using a *multi agent* approach whereby individual agents with in built behaviours are identified and mapped to a scenario. Some preliminary ideas are presented in this regard, with the thought that further developments can be readily incorporated into scenario data structure described earlier.

TASES found its first application within the VLEEM (Very Long Term Environment Energy Model) research theme, initiated by the European Commission in 2000. TASES was used to investigate pathways to a desired future energy economy using a back casting methodology. The project was undertaken using the methods described in this thesis.
An illustrative scenario is presented comprising the existing UCTE (Union for the Coordination of Transmission of Electricity) grid with a high proportion of renewable energy added. Using the simulation ability of TASES, estimates are made regarding complementary transmission and storage required.
A further illustrative example uses linear optimisation to quantify the competition of PV (photovoltaic) panels in the context of geographical dependency.
One of the most interesting application domains for this style of modelling is the study of global electricity grids. This configuration is examined for a case with a high proportion of renewable energy. Linear optimisation is also used to investigate the competitive limitations of a global grid with fluctuating renewable energy deriving from wind and sun.

The TASES model was applied to various energy system scenarios using simulation methods, sometimes in combination with linear optimisation, and found to produce useful results. The overall significance of this modelling approach is the more or less novel use of high temporal and spatial resolution together to describe dispersed energy systems. The approach allows a wide range of system types to be studied and is particularly suitable for systems which contain a high percentage of renewable energy technologies.

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Chapter 1

Introduction

The investigation of energy systems may be motivated by a multitude of reasons. One clear concern is the expected and even observed global warming effect (see figure 1.1) for which the energy consumption of the industrialised world is mainly responsible.

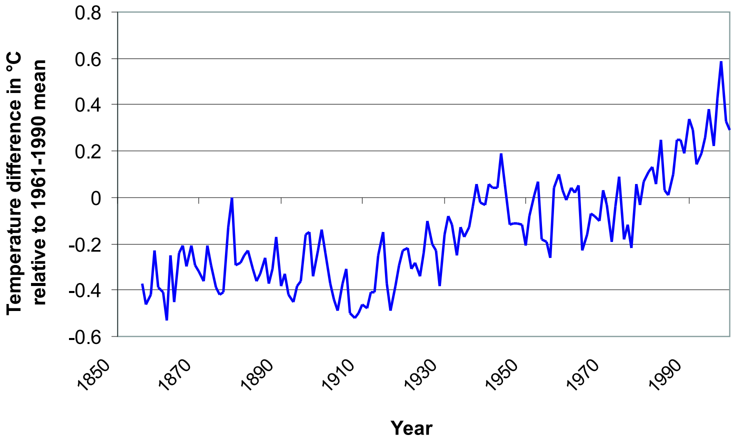


Figure 1.1: *Global annual temperature anomalies relative to the 1961-1990 mean* [CDIAC, 2001].

The global energy system relies to nearly 90% on fossil fuels. The problem is caused by the use of fossil fuels. It is common agreement that the combustion of fossil fuels and the consequent emission of carbon dioxide has an impact on the climate, not to mention the fact that fossil resources are both non-renewable and will be depleted within the 21^{st}–century. In addition, fossil resources are not uniformly distributed over the globe.
The importance of energy in its various forms to our modern civilisation cannot be

overestimated. Our complete urban settlement structure depends on an operating symbiosis with the surrounding hinterland, if only in respect of material flows, and is supported by the uninterrupted availability of energy. The continually increasing dependency on information technologies as well as major parts of our social behaviour and living standards are founded on the cheap and easy access to energy resources.

It is more or less obvious that the situation accompanying unilateral dependency on one form of primary energy – namely fossil fuels – and its geopolitical distribution implies a huge conflict and risk potential. This is not only related to the distribution of fossil resources but also to differing national assessments of likely climate impacts and their prevention. The first international efforts to tackle this challenge resulted in the ongoing Kyoto–process. The entry into force of the Kyoto Protocol would be a first step towards a sustainable future but there is currently no guarantee that this will occur.

The reasons above together with a growing world population that expects a continual increase in living standards means that the future will not lead to a decrease in final energy needs. Hence the only way to bring about sensible change in the energy economy will be to address the supply side.

Even in the event that energy needs rise by more than a factor of 10 and that conventional energy resources, restricted by depletion, are abandoned, there will always be enough renewable energy potential to meet future needs (see table 1.1).

Global physical potential of renewable energy sources	
Energy source	**Potential in consumption units 1993**
Solar insolation	**2 850**
Wind power	**35**
Biomas	**10**
Hydro power	**1**
total	**2 896**

Table 1.1: *Available potentials of renewable energy sources after* [ISE, 2001]

This outlook in combination with the fact that about 2 billion people have no access to electricity [WCED, 1987] is motivation enough to investigate the issue of renewable supply. So the challenge can be defined – with respect to the introductory quotation – as the aim to satisfy everybody's needs without violating the right of future generations to have the same possibilities.

The simplicity of the problem – as formulated by the German foreign minister

Joschka Fischer – *"without sustainability, no peace"*[1] – belies the difficulty of its solution.
Nevertheless there are numerous ideas how to tackle this problem. These vary from huge solar farms in sunbelt regions of the earth linked globally and using hydrogen as a secondary energy carrier to nuclear futures dominated by fusion technologies. Many are technical feasible even now. But to bring them into market and make them economically competitive is another matter.

One frequently raised scenario is that of a future hydrogen economy. The vision implies that all energy needs are satisfied via the secondary energy carrier hydrogen. This scenario is finding an increasing discipleship, chiefly headed by Jeremy Rifkin [Rifkin, 2002]. Rifkin favors an energy economy, dominated completely by hydrogen.
Such visions may represent the beginning of a change in the way future energy economies are considered, based on questions of necessity. But there is no real idea about the technology diffusion processes involved, how innovations come to market, and the accompanying feasibilities and risks.
That is the point where numerical modelling can contribute. In light of this challenge, modelling can evaluate possible development paths and provide a basis for sound decision making with regard to future project planning for the energy economy. Admittedly the time scale for these decisions and the related impacts and risks take place over a 100 year range and beyond. In particular, the global warming effects discussed earlier require modelling horizons in this range.

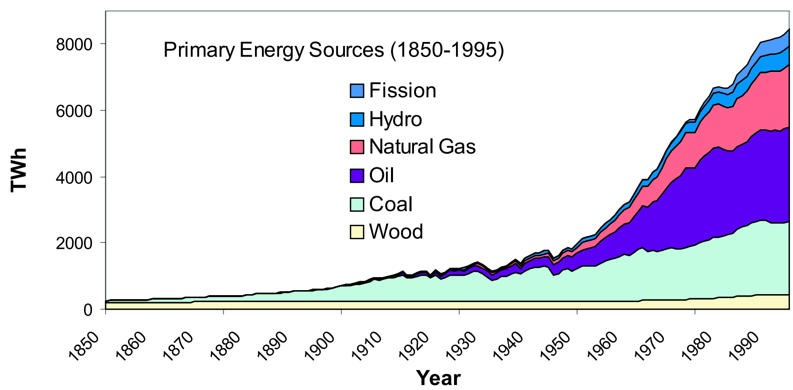


Figure 1.2: *Historical development of primary energy sources.*

Reviewing the historical development (see figure 1.2) of primary energy sources, it

[1] Joschka Fischer (German foreign minister), March 2002, Hydrogen–congress in Berlin

is not only obvious that total demand is rising quite fast but also that market shares are diversifying. One objective of global modelling is to update this kind of diagrams in order to help guide public policy development.

The purpose of this thesis is to establish a strongly technical modelling approach, which is able to capture issues commonly neglected in other forms of modelling. In particular, geographical and time–dependent impacts can have a major influence on the engineering feasibility or economical acceptance of a particular set of scenario assumptions. Hence, this thesis seeks to develop a modelling approach which can satisfactorily treat such dependencies *and* deal with long term issues.
The declared outcome of this work is to demonstrate the necessity of this new modelling approach and to establish an initial proof-of-concept application. The novel aspect is to be able to model renewable energy technologies alongside conventional technologies, given that renewable technologies are expected to play a significant role in future energy economies.

Attempts to model future energy economies have a strong and honoured history. Concerns about future global energy supply and demand balance have been addressed since the very early days of economic science. Famous names in the field include Jevons (1865), Arrehnius (1896), Hubert (1959) and Meadows (1974) [Meadows, 1974]. Each of their studies have correctly pointed out, at an early stage, many of the relevant problems mankind is facing today.

Finalising with a quotation from Mahatma Gandhi – *"The difference between what we do and what we are capable of doing would suffice to solve most of the world's problems."*[2] – with our purpose to reach a sustainable future. This future is never a fiction as long as the will to bring about a change is present. Numerical models and the understanding they provide may be a first step in the challenge to reach this aim. Such models can help us find the right path.

[2]Mahatma Gandhi – Indian politician and social activist, 1917-1985

Chapter 2

Fundamental issues regarding energy system modelling

2.1 Introduction

First the question should be raised, what is meant by the terms model and energy system.
A *model* is a simplified description of the reality with the purpose to highlight certain relations and to make the best prediction of future developments possible. In practice this means that the scope and structure of the system must be identified and then the rules governing the system behaviour must be uncovered.
The normally huge complexity of real systems requires that a simplification in modelling tasks is unavoidable. The choice of this simplification contributes greatly to the validity of the model.
In the case of *energy systems*, a model is defined as a framework of relations, be they technical, economic, or social, which describe the actual processes under investigation. The quality of such a model is determined by the degree to which this aim is reached.
The purpose of a model is, first and foremost, to aid the understanding of reality. This includes the actual current and historical functioning of a system as well as its future development.
A successful model offers the possibility of making forecasts of future system patterns in relation to expected or desired outcomes. Therefore, the central issue is to better understand the important causal relations involved.
With regard to the complexity of most energy systems, building such models can be both a challenge and a tremendous effort. To identify all the different details is, in general, a hopeless task. In order to gain suitable results, a certain specialisation in the modelling approach has to be defined. The emphasis can focus on, for example,

engineering, economics, or environmental science. This choice of focus gives rise to different modelling approaches.

2.2 Classification

The modelling of energy systems is an endeavour that looks back on a tremendous growth process in recent years. This tradition has yielded a considerable number of different modelling approaches and therefore a systematic classification is useful. Past experience has led to an informal consensus for classifying energy models using the following *dimensions* [van Beck, 1999]:

1. *Purposes of the model*
   general and specific purpose: consulting, plant commitment, etc.

2. *Model structure*
   internal and external assumptions

3. *Analytical approach*
   top-down versus bottom-up

4. *Methodology*
   economic equilibrium, simulation or optimisation, multi actor, backcasting

5. *Mathematical approach*
   linear versus dynamic programming, e.g. evolutionary approaches

6. *Geographical coverage*
   global, regional, national, local or project level

7. *Sectoral coverage*
   energy sector and all other influenced sectors

8. *Time horizon*
   short, medium and long-term

9. *Data requirements*
   qualitative, quantitative, monetary, aggregated, disaggregated

When faced with the first four items, the following question comes up: *What relevant processes are acting on this system and what are the rules these processes follow?* The selection of key processes and the encoding of rules to describe these processes is both a challenge and the subject of ongoing research and development. These issues are most responsible for reproducing the immanent system dynamics in a suitable

Existing Energy Models		
Model	**Developer**	**Methodology**
EFOM-ENV (Energy-Environmental Flow Optimisation Model)	European Commission DDG-XII F/1, Belgium	Optimisation
ENERPLAN	Tokyo Energy Analysis Group, Japan	Econometrics and simulation (depending on mode)
ENPEP (Energy and Power Evaluation Program)	International Atomic Energy Agency (IAEA), Austria	Macro-economic for demand, economic equilibrium for total energy system.
LEAP (Long-range Energy Alternatives Planning)	Stockholm Environmental Institute Boston, USA	Demand: econometric or macro-economic. Supply: simulation
MARKAL (MARKet ALlocation)	International Energy Agency (IEA)/ ETSAP	Toolbox/ Optimisation
MARKAL-MACRO	Brookhaven National Laboratory, USA.	Macro-economic for MACRO and partial equilibrium through optimisation for matching demand and supply in MARKAL.
MESAP (Modulare Energiesystemanalyse und Planung)	IER, University of Stuttgart, Germany.	Econometric (demand), simulation or linear programming (supply).
MESSAGE-III	International Institute for Applied System Analysis (IIASA), Austria.	Optimisation.
MICRO-MELODIE	CEA, France	Macro-economic based on price equilibrium.
RETscreen (Renewable Energy Technology)	CEDRL/Natural Resources Canada	Spreadsheet/ Toolbox.

Table 2.1: *Established main energy models as listed in* [van Beck, 1999].

manner. Forecast models, in particular, require that the embedded dynamics are representative.

One common strategy to address such issues is the so-called *Neoclassic*. The core feature of this economic theory is that a given economic system is in a global optimised state at any time. This implies a global knowledge that is available to all processes. In reality, this assumption is questionable because each process acts with only a limited knowledge.

On the other hand, new approaches are being developed within evolutionary economics. Evolutionary economics assumes only a limited knowledge for each process, in what leads to potentially suboptimal system behaviour. The resulting dynamic is possibly a more suitable representation of real system behaviour. A completely different approach is chosen within the VLEEM project, as explained in section 3.4. Briefly, VLEEM starts from especially designed future states, which fulfill certain sustainability criteria and traces this future state back to the present situation.

With regard to the increasing importance of energy within our society and the accompanied problems of security, the need for energy models is significant. Over time, a number of energy models have been developed by various institutions world-wide, as shown in table 2.1. These models are highly diverse in their approach.

The TIMES model is broadly representative and will be examined more in detail in section 3.1.
All the models listed stress in their implementation a neoclassical approach and a high level of geographical aggregation. These decisions may be appropriate with reference to their stated purpose, but nonetheless there are advantages in leaving this path of modelling and attempting something new. The VLEEM project dictated that a different approach be developed.

Hence the exploration of new methods is central to this thesis.

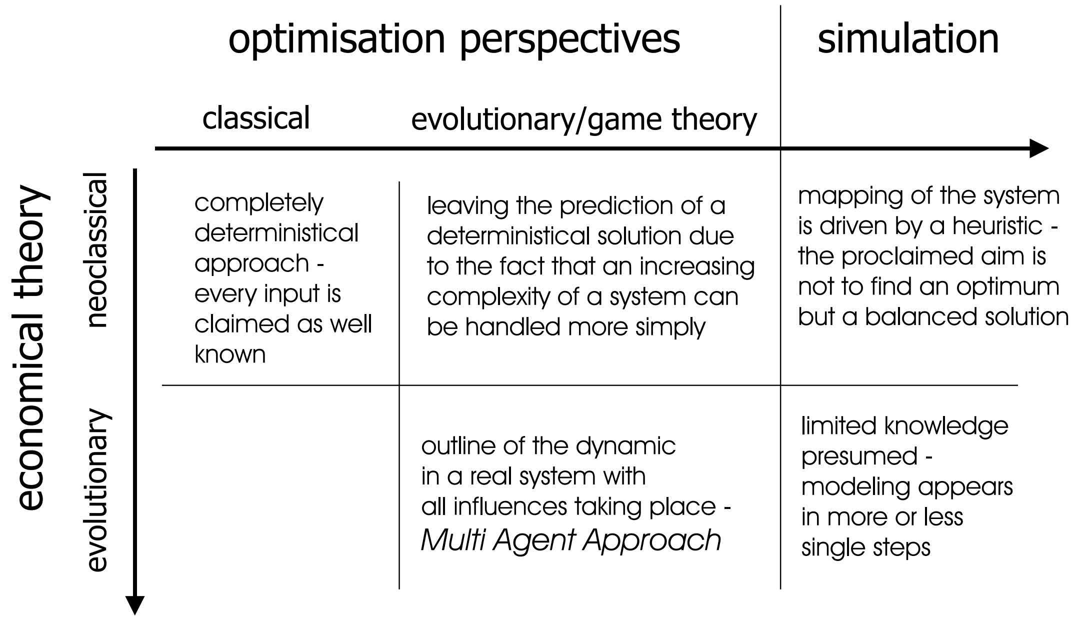


Figure 2.1: *Matrix of the different modelling assumptions used by different methodical approaches.*

Figure 2.1 gives a characterisation of the different perspectives investigated in this thesis. The vertical axis depicts the economical theory chosen for the modelling approach while the horizontal axis outlines the mathematical approach relevant to the modelling issues under consideration in this thesis. In addition a pure simulation approach is also followed. Optimisation, in this case, is either based on linear programming solutions or on evolutionary optimisation solutions. Corresponding to this matrix, the following items are traversed within this thesis:

- Simple heuristical simulation based on energy flow calculations for the complete system. All parameters are fixed, supplied from outside and taken to be optimal.

- The complete system is described by linear relations and will be optimised according to an objective function (e.g, least cost).
- The system relations are specified externally and are rather complex. Optimisation is done by evolutionary processes.
- Various possible development paths are identified by modelling single point-in-time steps along this path. This is the approach used in the VLEEM project (see section 3.4).
- The previous point indicates a range of complying development paths can be obtained. Qualifying these paths leads to an optimal development path.

The intended purpose of the matrix in figure 2.1 is to locate new modelling topics, motivated either by the underlying methodological assumptions or by a mathematical approach which allows one to map the intrinsic system dynamics.

2.3 Mapping of energy systems

In order to map a system, simplifications are necessary. Simplifications mean, that not all dimensions of the problem will be covered and that the scale of complexity is sufficient to answer the underlying questions, but keeps the problem as simple as possible. In the case of energy systems, two entities will be distinguished:

- *commodities*
- *processes*

Commodities cover all kinds of different things: materials, energy carriers, money and pollutants. Those commodities involved with the system under investigation need to be identified and mapped. The transformation and storage of these commodities are undertaken by *processes*. Within this simple picture, it is possible to model the complete chain from mining to energy needs. The combination of these items provides the ability to sketch any sequence of transport and transformation within an energy system. The visualisation of these steps in a particular scenario, is mostly done in a manner outlined in figure 2.2.
A commodity is represented by a bus which collects all ingoing and outgoing connections to the associated processes. This process, in turn, can combine several commodities by assigning certain conversation or storage facilities.

The numerical depiction of these commodities and processes in a sophisticated manner presents a real challenge. The aim is to provide a high flexibility in the underlying

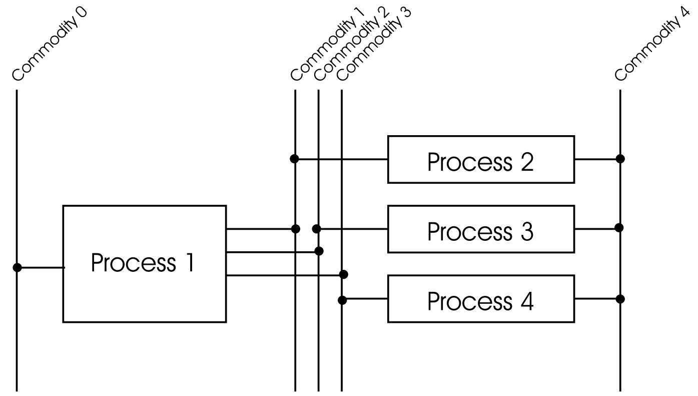


Figure 2.2: *A common visualisation of energy systems for modelling purposes established by M. Beller* [Beller, 1975]. *Commodities are represented by horizontal lines connected via processes (rectangles) to other commodities.*

datastructure in order to map all systems, but nevertheless be able to manage the data load. An acceptable solution can be, of course, strongly dependent on the system to be described. But a more generic approach is required. Therefore two possible approaches are considered. The first arises from the economic description of the system – the so-called *top-down* approach – and the second comes from a more technical description of the individual processes in a system – so-called *bottom-up*. Neither the first nor the second is suitable to map a real system alone. That is the reason why a mix of both approaches is often chosen.

2.3.1 Idea of mapping space and time resolution

The model approach developed in this thesis arises from the VLEEM project initiated by the European Commission. In this project, a number of scenarios on different time and geographic scales are prepared and analysed using TASES.

As discussed earlier, a core theme in this work is the combination of an arbitrarily precise geographical coverage, perhaps comprising the entire planet, and a very high time resolution with regard to selected processes.
As might be imagined, this approach contains a high degree of modularity, a feature which can be used to manage the huge amount of data involved.
The modelling environment TASES (Time And Space resolved Energy Simulation) implements many of the concepts introduced thus far in this chapter in an integrated way. TASES itself is described in some detail in appendix A.

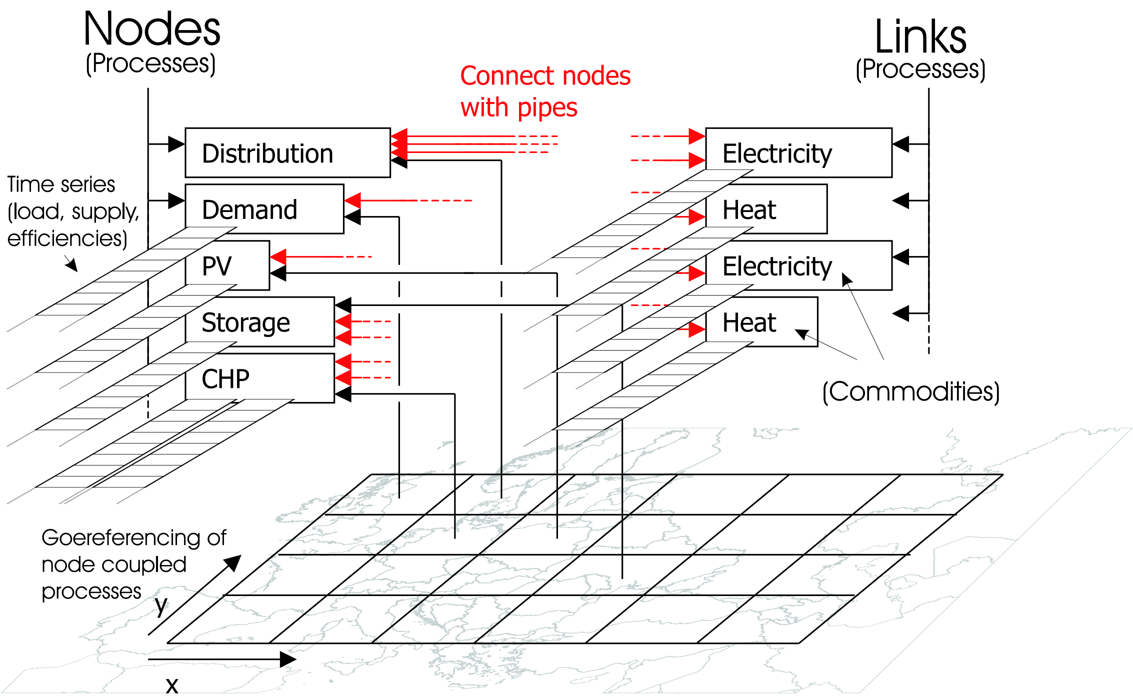


Figure 2.3: *Indicative implementation of the geographical coverage for modelling purposes. Fixed location processes are linked to an imagined, the region of interest covering grid, and they are also linked to the interconnected processes while each process administers its own time resolution and time series data.*

The underlying data model relevant to the data structure is outlined in figure 2.3. With regard to the spatially disaggregated model approach that is being developed, two different entities can be distinguished – fixed location entities and interconnecting entities. Therefore, within the model implementation, two lists called *Nodes* and *Links* are maintained. The *Node*–list collects fixed location processes such as conversion, supply and demand patterns as well as various kinds of storage and distribution patterns taking place in a given scenario. And the *Link*–list collects transmission processes which represents a connection of a pair of nodes.

This includes all kinds of pipes, transmission lines and other transport infrastructure regarding the flow of material or energy. The spatial resolution of the scenario is represented by a two dimensional array. Each field in this matrix corresponds to a geographical area. The time resolution is managed within individual processes through the use of time-series.

In TASES, the complete data management is organised using three different modules (see figure 2.4). The key module is the *Graph*–module, which also bundles the complete main data management procedures. Included in this module are two sub-

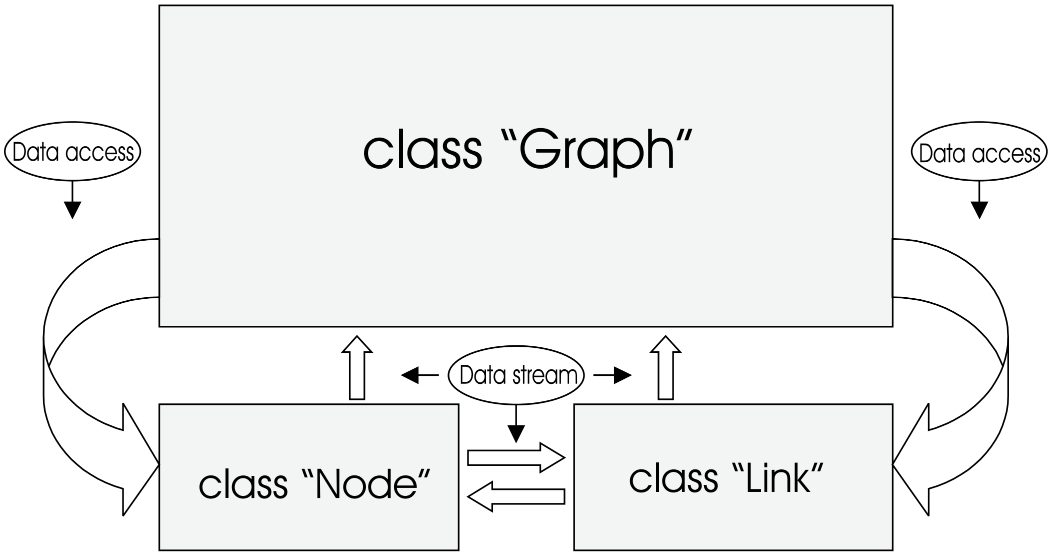


Figure 2.4: *Modular class structure on which the software data model is based. The three modules communicate due to the outlined streams and manage the complete data handling.*

modules called *Node* and *Link* which are the data structure for the contents of the above-mentioned lists. Data relating to individual processes, such as efficiency values, costs, emission rates, and so forth, are managed by those processes themselves. With regard to the spatial pattern, these items are symmetrically linked with each other. The surrounding main module has fast access to the entire nested data base through use of efficient indexing.
The purpose of the data structure represented *Graph* is to contain a scenario – that is to map a real system (or some variant) to its numerical representation, as indicated in figure 2.5. The complete geographical pattern as well as a predefined time resolution is determined by the modelling effort. This means that all geographically related individual processes have to be considered in a spatially disaggregated manner along with any associated consequences for the complete system. In addition, any relevant time relations arising from the predefined time resolution need to be finalised. This is managed through time-series provided to each process that shows a certain time-dependent behaviour, for instance, a predefined consumption load series or the supply behaviour of a highly time intermittent renewable energy technology.

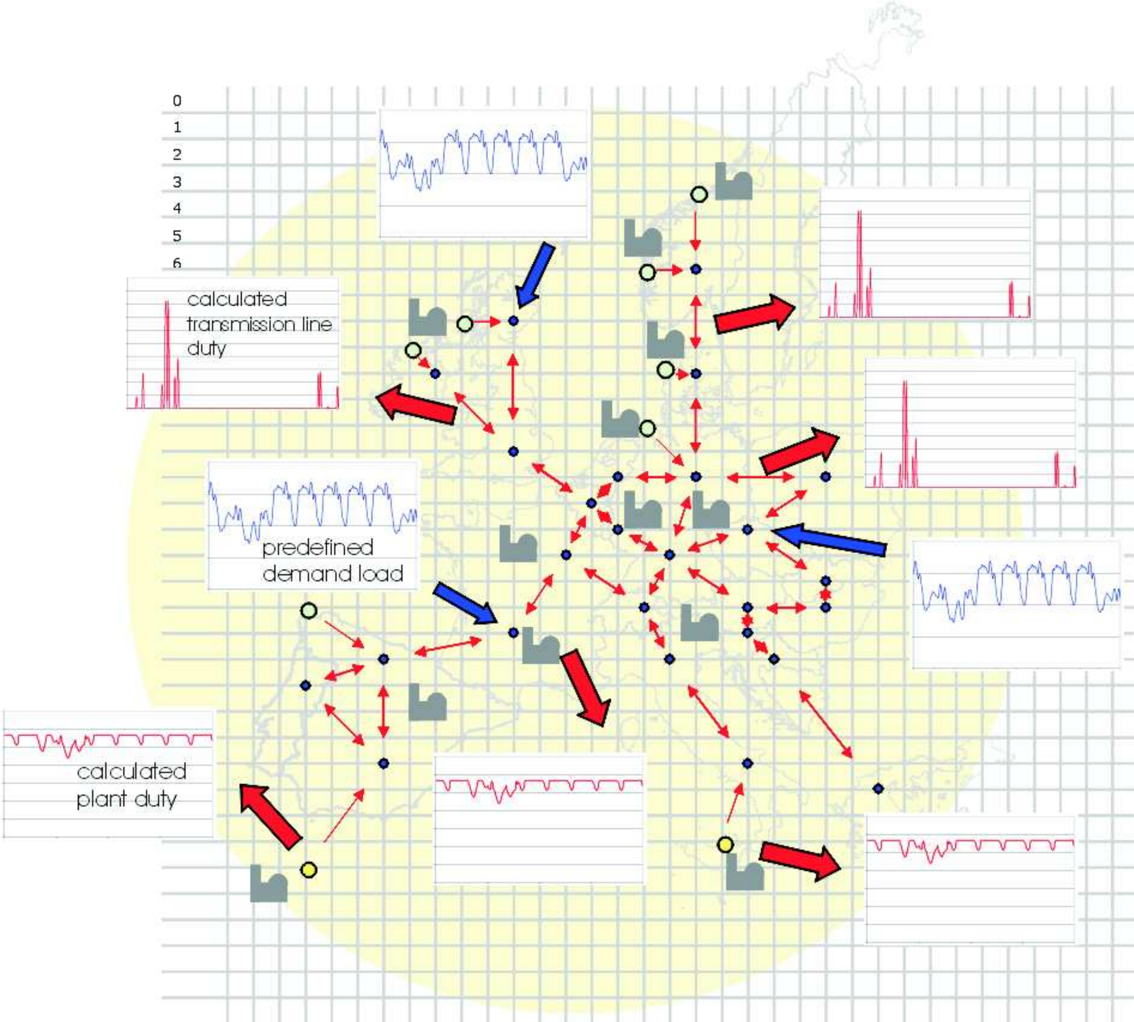


Figure 2.5: *A representing example for a modeled scenario with all in- and output facilities (marked by arrows). The complete system is considered with all geographical dependencies and time relations.*

Depending on the selected mode of use – as described in the following sections – load curves for each process and connection are created during the modelling run with TASES.
In general, the emphasis in this special approach is to depict all potential flows in an energy system with their intrinsic time dependencies.

Chapter 3

Different modelling approaches

3.1 The TIMES model generator

TIMES (The Integrated MARKAL-EFOM System) is a model generator for representing, optimising, and analysing energy systems on flexible time and regional scales. The TIMES model generator has been developed under the auspices of the International Energy Agency (IEA) within the Energy Technology Systems Analysis Program (ETSAP). The TIMES development pursues the goals of merging the advantages of existing energy system models like MARKAL and EFOM, of eliminating some short–comings in these previous models, and of creating a modelling environment able to adapt to new ideas and methodologies. It has been implemented in the equation-based modelling language GAMS (General Algebraic Modeling System). The model has been designed for the long-term analysis of energy, environmental and economic (E3) issues over a time-horizon ranging from years to decades. Typical questions analysed with such a model are, for example, the assessment of greenhouse gas abatement strategies or capacity expansion planning in the electricity sector [Fahl, 2004].

TIMES follows the so-called bottom-up systems engineering approach that allows a detailed technical description and economic evaluation of the energy technologies in question based on a *neoclassical* approach. The energy system modelling approach used by TIMES can be divided into four parts topology, numerical data, mathematical structure, and scenarios. Due to this division and the generic formulation of the core model equations, the TIMES methodology is intended to be easily applied to different case studies ranging in scale from municipal energy systems to multinational energy system. Therefore, TIMES can be considered as a model generator, in the sense that it provides a software environment for generating specific models.

3.1.1 Structure of a TIMES model

The structure of TIMES is sketched in figure 3.1. First a model of arbitrary complexity is sketched and translated to the special modelling language, which is very close to GAMS coding. This code is then handed over to a preprocessor, which produces the final GAMS code. The code is then translated to an optimisation problem and handed over to a special optimiser. The complete processing sequence is outlined in figure 3.1.

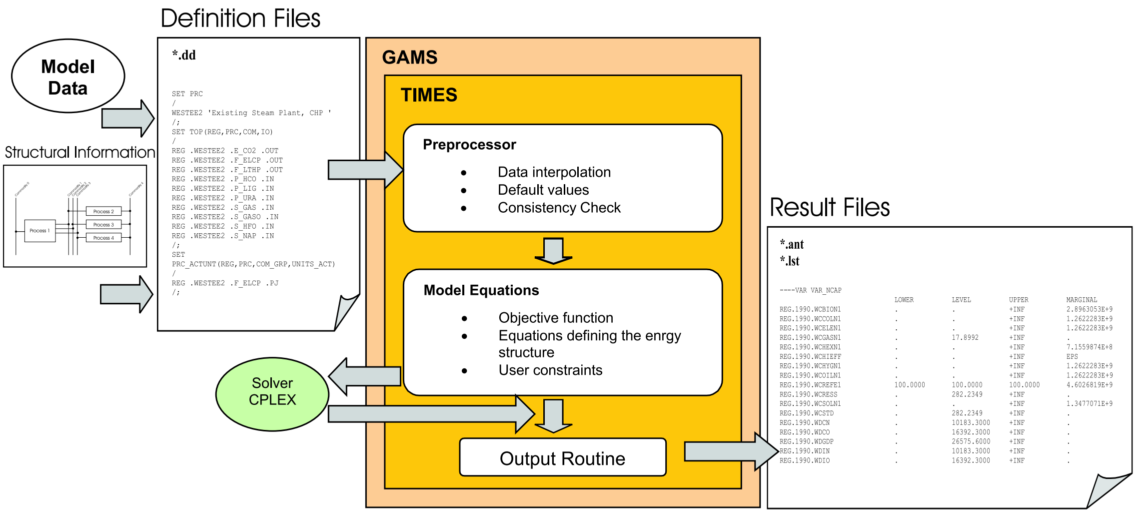


Figure 3.1: *Schematic visualisation of the* TIMES *modelling framework* [Eherer, 2003].

TIMES has no explicit geographical referencing scheme, still it is possible to define so called multi-regional models. Under this concept, different regions within one model, are applied to different markets but not for reasons of spatial differentiation (see figure 3.2).

The design ethos of TIMES is to support a regional distribution for reasons of local markets rather than for engineering and geographical effects. The regions are connected by inter-regional exchange processes describing the trade activities between the various internal model regions and these are then modelled over the same time horizon divided into an arbitrary number of periods to represent average years. Milestone years and past years can also be defined in order to calibrate a particular model.

To help address the sub-annual fluctuation behaviour of single processes, that is those which cannot be adequately mapped with cumulated annual values, TIMES provides a four hierarchy level of timeslices to handle seasonal and diurnal variations within the system.

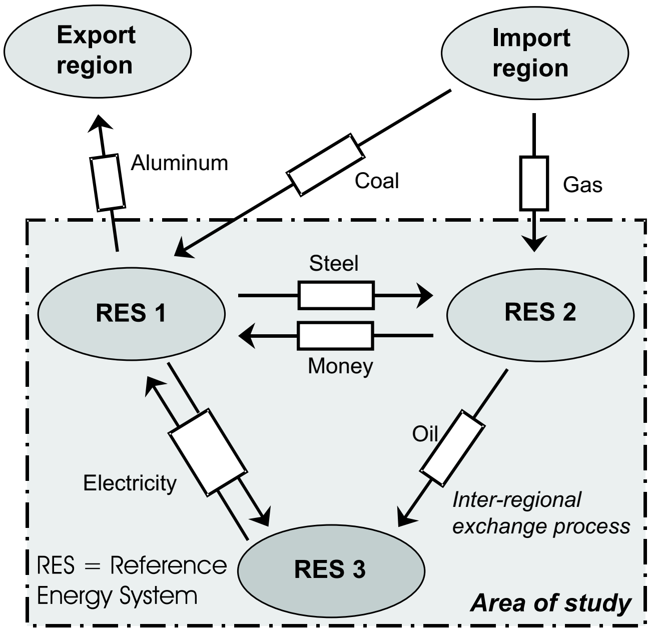


Figure 3.2: *Example of a multi regional approach in* TIMES*. The regional distribution is designed to support local markets rather than engineering and geographical effects* (source [Mäkelä, 2000]).

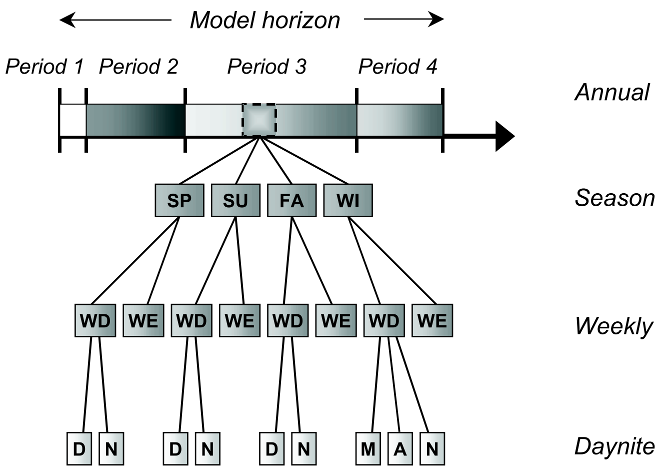


Figure 3.3: *The timeslice tree of possible subannual time divisions in the modelled time horizon* (source [Mäkelä, 2000])*. The time resolution is fixed to these discrete time patterns.*

This four levels are ANNUAL, SEASON, WEEKLY and DAYNITE (see figure 3.3). Each year can be divided into four seasons and further subdivided into typical working days and weekends, and then day and night profiles.

Using this breakdown, a TIMES model can be developed with all numerical information given as scalar parameters. An detailed description of TIMES is provided in [Mäkelä, 2000].

3.1.2 Example model generated in TIMES

To illustrate the capabilities of TIMES, a simplified scenario concerning the future energy economy in Spain is provided. The example results from a workshop dedicated to the fundamentals of TIMES [TIMES Workshop, 2003].
The design of the energy system is shown in figure 3.4 using the accepted notation.

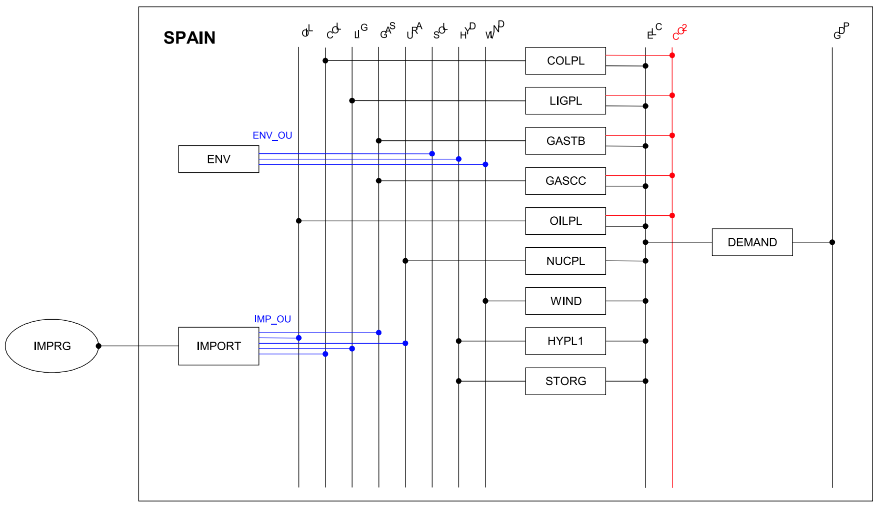


Figure 3.4: *Assumed hypothetical scenario pattern of the Spanish energy economy as a modelling exercise.*

The idea behind this example is that energy demands are driven by GDP (Gross Domestic Product). The demand sector is just represented by a single factor converting the GDP to electricity demand. The conversion sector is represented by the following processes:

- oil, hard coal and lignite power plant (OILPL, COALPL, LIGPL);
- gas turbines and combined cycle plant (GASTB, GASCC);
- nuclear power plant (NUCPL).

Input data for Spain TIMES model				
Year	2000	2010	2020	2030
GDP in 10^9 €$_{2000}$	612.2	842.7	1088.7	1406.5
Efficiency (1 TWh produces x*10^9 €$_{2000}$)	3.123	3.196	3.284	3.448

Table 3.1: *Input assumptions for the milestone years based on data from* [INE, 2003][Eurelectric, 2001].

These processes are connected to primary commodities representing non-renewable in nature, or renewable sources, here

- wind power (WINDT);
- running river and retention hydro power (HYPL1, STORG).

The non-renewable resources and the renewable sources are modelled in a different fashion.
On this basis, the modelling purpose is as follows: *to find a certain development forecast based on the existing capital stock of power plant and assumptions for GDP growth*. The modelled time horizon is restricted to 2030 and modelling time slices are ten years, starting from 2000. This means that all input data for the model has to be forced to this pattern. The projected GDP growth is outlined in table 3.1. All information supplied exogenous to the model has to follow the ten year time pattern.
In addition to these constraints, the objective function is also forced by the parameters, defining the stock of processes at preselected milestone years. In general, the parameters are:

- investment, maintenance and operation costs;
- efficiencies;
- availabilities;
- economic and technical life time.

The assumptions made for these parameters for a single milestone year are collected in [TIMES Workshop, 2003]. To obtain a realistic scenario, the existing power plant stock has to be given as input to the model. Therefore all the infrastructure and power plant commissioned in past decades and still operational need to be included. These assets are outlined in figure 3.5.

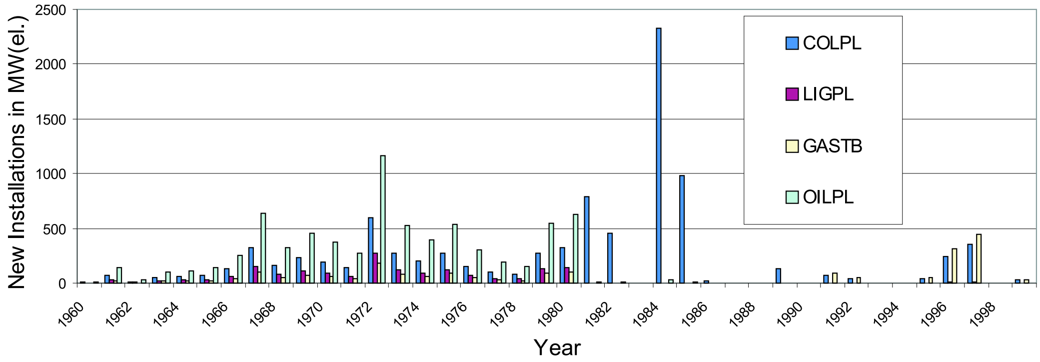


Figure 3.5: *History of previously commissioned infrastructure that may have an impact on the time range to be modelled.*

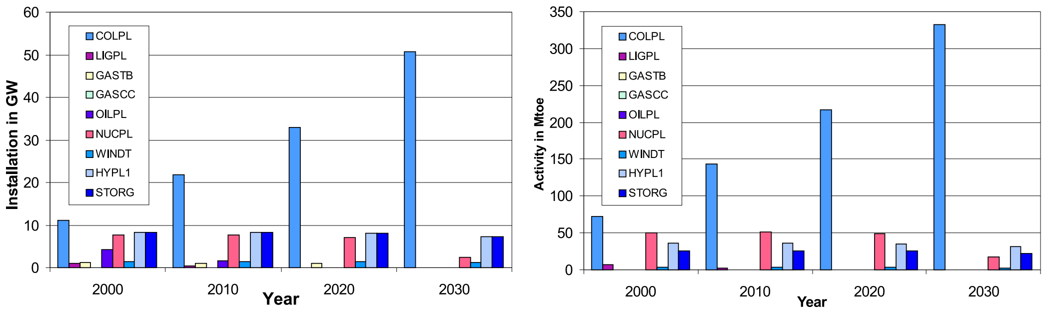


Figure 3.6: *Projected installations and activities for Spain until 2030. These arose form the modelling process described in the text.*

The output of the TIMES model tells, when new capacities should be installed and in which mode they should be operated. The precision of the later advise depends of course on the time resolution of the model. The results for this scenario are outlined in figure 3.6 in highly aggregated form.

The technology of choice in this special prepared scenario are hard coal fired power plant. In 2030 this technology cover about 80 % of the electricity market. Only small slices of renewable energy technologies and nuclear power stay competitive. This result is caused by the predefined specific cost assumptions, which favor on a thirty year time scale this outcome as the most competitive one.

Certainly, such results have to be evaluated very carefully because of the very strong dependency on input parameters. This modelling example was selected to give an impression of TIMES and to help indicate some differences with regard to other modelling approaches in this context.

3.2 The attributes and limitations of TIMES and related approaches

The choice of the time horizon is certainly crucial for a lot of questions addressed with energy models. As can be demonstrated for example with IEA Energy Outlook the change on a global level is hardly visible in energy studies covering the next 20 years. It seems as if the system keeps ongoing like in the past. Therefore it was decided to address a much larger time horizon in VLEEM. But the question comes up:

Is it possible to obtain reasonable results from an energy investigation looking over a 100 year time horizon?

Energy models like TIMES, assume perfect foresight, all future developments are determined – like in classical mechanics – by the initial state and the set of development equations. The development is actually modelled by an optimisation process. A possible extension is the introduction of stochastic modelling, which add uncertainty to the results.
In practice most studies do not present one possible solution but a set of solutions mostly named scenarios.
Nevertheless there are other useful ways of dealing with large time horizons, up to 100 years. One possibility is *backcasting*, discussed in more detail in chapter 3.4. Backcasting starts with the expected or desired endpoint and then identifies trajectories which work back to present.

A further limitation of the established models discussed above is the poor consideration of geographical coverage. This is no longer possible in long term models, if a proper representation of renewable energy resources becomes crucial. This impacts in the same manner the representation in time.
This is also strongly correlated to a claimed high time resolution in the modelling approach. Normally, most models, including TIMES, work with average values for highly fluctuating commodities.
For instance, here is how TIMES deals with peak load conditions as outlined in figure 3.7. An additional user defined multiplier relative to the average load behaviour is used to estimate the peak requirements. This approach is not particularly suitable for volatile demand pattern and supply pattern. In particular it does not take into account fine grained differences in supply and demand mismatch across different locations (see figure 3.8).
Depending on model size and complexity, geographical location patterns and a couple of other influences, process related load curves can work together or against each other. Neglecting of this behaviour by only handling average values may lead

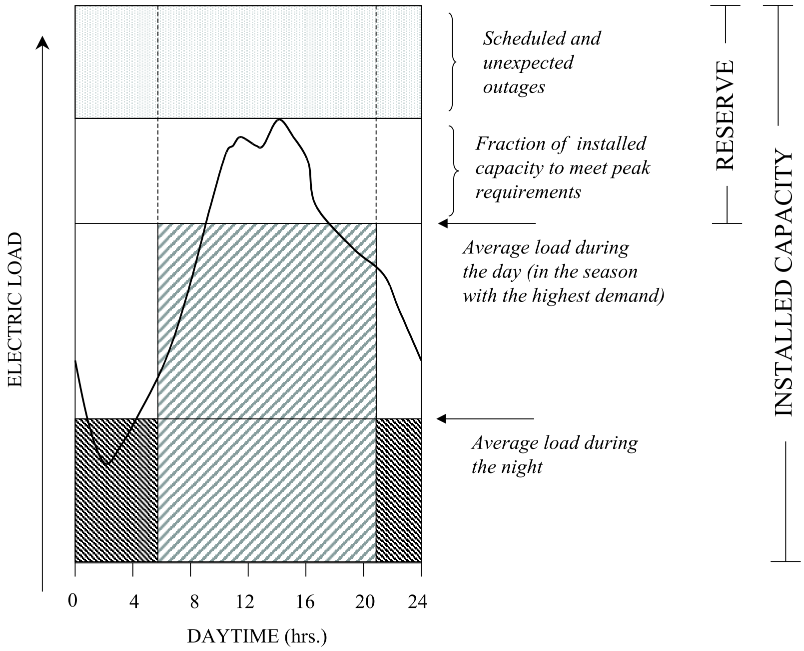


Figure 3.7: *Support in* TIMES *for highly time variable commodities* (source [MÄKELÄ, 2000]*). The load curve will be represented by periods with average values and peak conditions are handled by simple multipliers .*

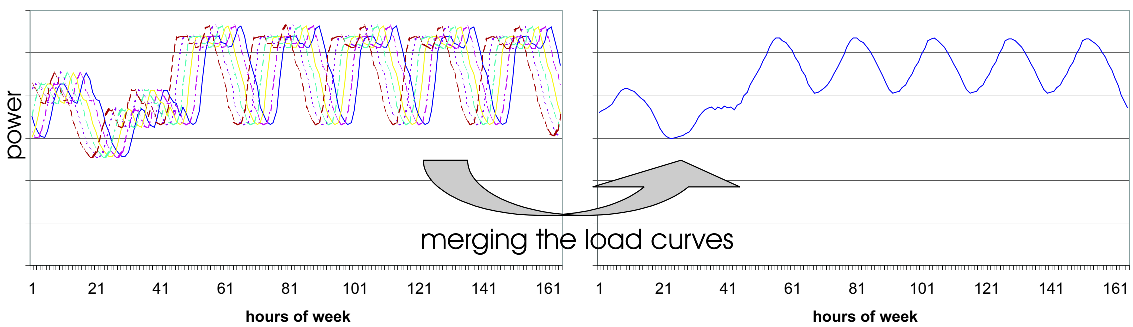


Figure 3.8: *On the left hand side five possible load curves with a location dependent time shift are depicted. If they are connected in a network they merge, due to compensation effects, to an average load curve at each location (right hand side).*

to erroneous results.
All in all, one very significant conclusion from the above discussion is that processes with a high degree of intermittency require modelling approaches which support high temporal resolution and precise geographic information.

The observations made above provide the cornerstones for this thesis. Firstly, TASES is specifically designed to support renewable technologies in particular through high temporal and spatial resolution. And secondly, the possibility provided by this design to model special system conditions, may support an early attempt in the field of energy economics to abandon the perfect foresight hypothesis and explore backcasting as a means of investigating long time horizons.

3.3 Stochastic *Multi Agent Models* as alternative approaches

A possible way to model decisions more realistically is a *multi agent* approach. A multi agent model is formally described by a list of agents a_i and for each agent by a list of possible strategies s_{ij}. These strategies are often influenced by stochastical driven processes.
Certainly such a procedure is not deterministic. But nevertheless the outcome may be, depending on the modelling purpose, more relevant.

The application of multi-agent models is not followed beyond this simple example. However, some back-of-the-envelope investigations are made in order to explore the potential of the method. These examples use the TASES data structures.
More specifically, a highly abstracted scenario matrix of *equidistant* consumers is assumed, who are supplied by two traders located at the opposite edges of this matrix. In the context of a multi-agent approach, due to the very simplified formulation, only two different patterns of behaviour will be identified – the consumer pattern and the trader pattern. In this arrangement each consumer and trader acts as an autonomous agent, duly influenced by their surroundings and circumstances (see figure 3.9).

In a first example two kind of agents are distinguished: oil traders and final oil consumers. Two oil traders occupying traders positions, who compete for customers. The have an oil storage, which allows them to wait for an optimal point in time to order oil. The constraints are, on one side the world market price for crude oil faced by the traders and, on the other side, the heat demand of the consumers. The

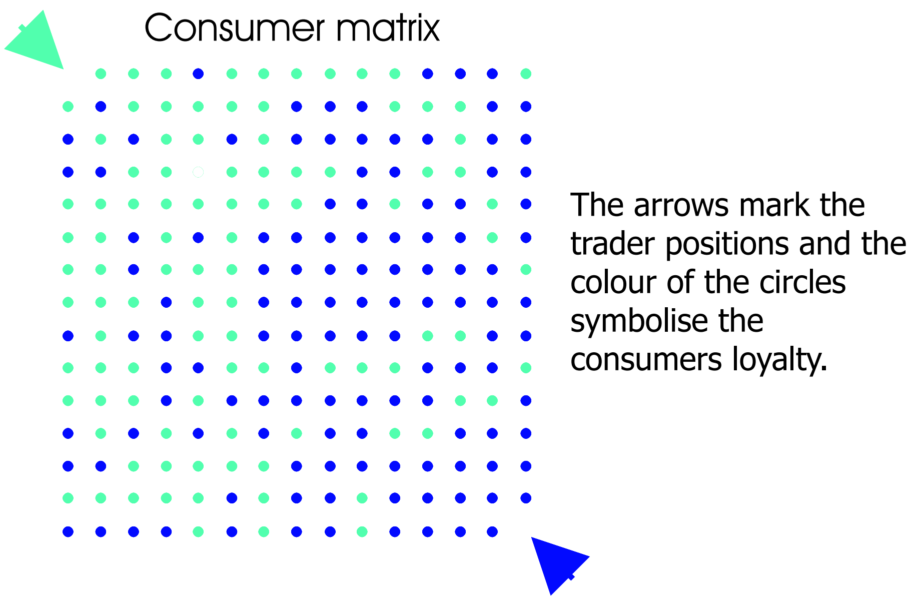


Figure 3.9: *A matrix of equidistant located consumers are supplied by two traders located at two opposite edges. The figure outlines the trade relations at one arbitrarily chosen time step.*

stochastic process is described by the following rules:

- *in the case that a consumer agent is acting*
  The price offered by a trader depends on the oil inventory held by the consumer and a loyalty attribute based on their last completed transaction. The purchase decision is stochastically determined.

- *in the case that a trader agent is acting*
  The trader restock decision depends on the expected future price of crude oil and a knowledge of consumer inventories. The actual decision is stochastically determined.

One outcome of the traders' behaviour is visible through their stockpile profile and their accumulated sales (see figure 3.10 left hand side). In addition, the geographical transactions over time enable the study of spatial trading patterns.

A second example is based on the same spatial arrangement as in the first case, but now the consumers buy electricity. Each trader offers electricity and operates an individual power plant mix with corresponding fuel costs. The uncertainty in the development is implemented in the following manner:

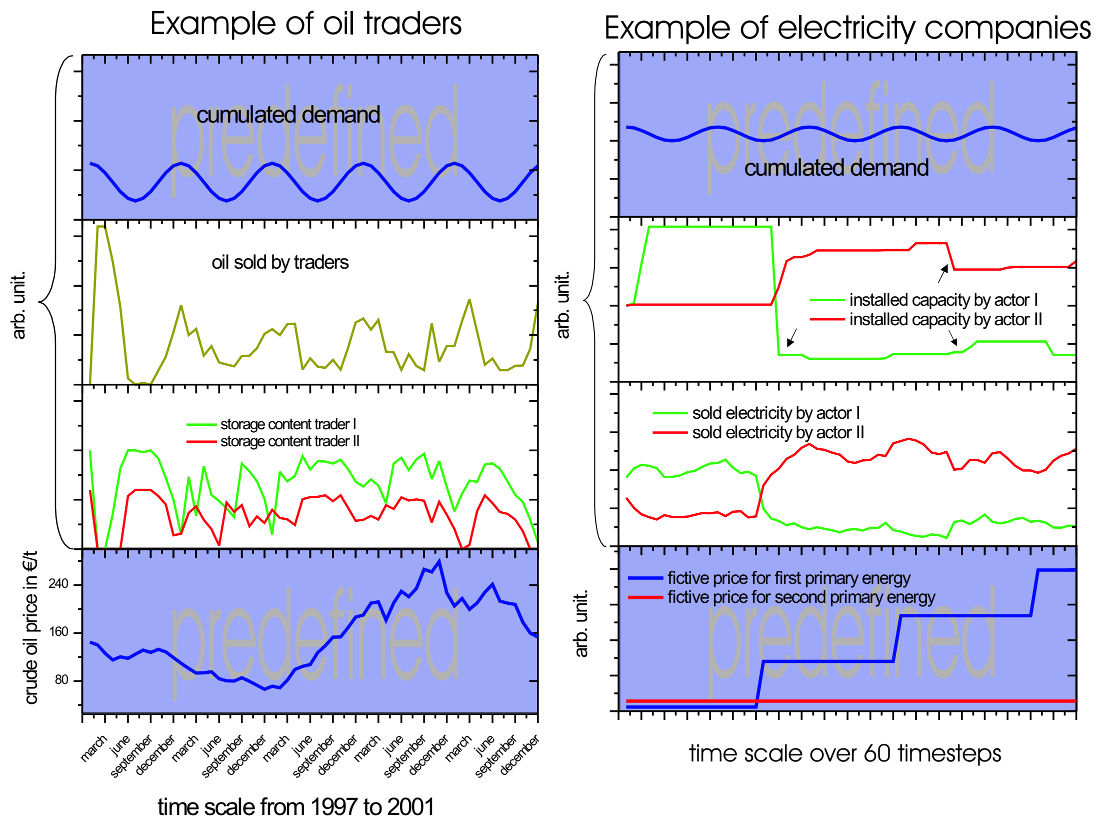


Figure 3.10: *Possible development path in the competition of oil traders (left hand side) and possible development path in the competition of actors on the electricity market (right hand side).*

- *in the case that a consumer agent is acting*
  The price of electricity offered by a trader depends on spatial considerations and the state of the existing trading relationship. The purchase decision is stochastically determined and the resulting contract cover the next time step.

- *in the case that a trader agent is acting*
  The decision to run a generation facility depends on the expected sales in the next time step and the running period of the individual plant. The commitment decision is stochastically determined.

In this scenario, one actor loses a lot of market share because of his increasing fuel costs due to the introduction of a hypothetical stepwise carbon tax. Later on, he commissions a new more efficient power plant to try to regain his earlier market position. The result of this investment can be studied by evaluating the resulting plant usage and trader sale figures (see figure 3.10 right hand side).

Clearly, these examples are not particularly sophisticated. They are primarily given to present the method. The methodology requires certain forecast assumptions in order to identify possible development paths. The purpose of this style of modelling is to examine transitions which may exist or appear within an energy system. More specifically, the range of phase transitions might be of major interest (see figure 3.11).

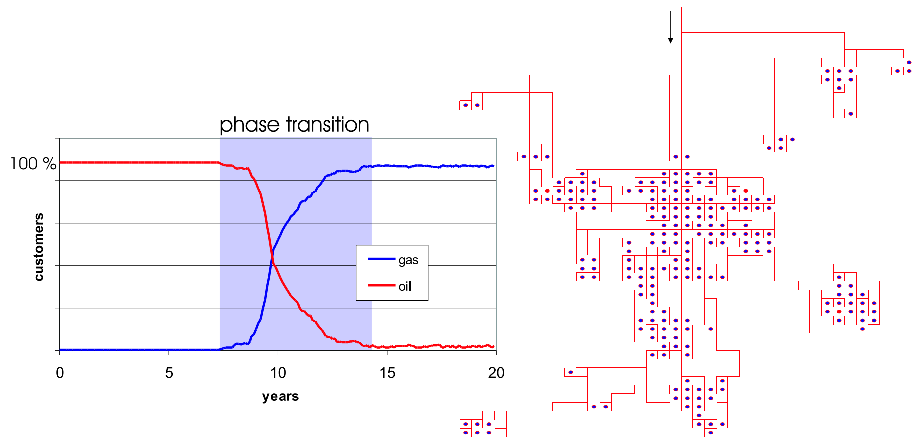


Figure 3.11: *Potential phase transition from oil to gas due to technology diffusion. The diagram shows the cumulative behaviour resulting from the spatial distribution of consumers as indicated and a possible growing gas grid which supplies a rising number of consumers.*

In the outlined example a very simplified transition from oil to gas in a district heating system is sketched. Regarded drivers for this diffusion process are spatial aspects as well as individual consumer depending decision patterns.

One challenge that can be tackled with a multi-agent approach is the quantification of causality underlying certain diffusion process. Extrapolating this idea, agents acting on an even larger scale (e.g. due to climate, politics, etc.) may also provoke a phase transition from a fossil-fuel-based economy to a hydrogen-based economy. Such issues are research questions in their own right and lie outside the scope of this thesis. The following section provides some initial thoughts on another novel approach.

3.4 VLEEM – a special long term modelling approach

VLEEM (Very Long-term Environmental and Energy Model) is a project initiated by the European Commission. As the name suggests, VLEEM is concerned with the development of energy systems on a very long term, that is up to one century.

VLEEM works with the hypothesis, that sustainable development becomes the dominant paradigm of national and international politics. This approach "simplifies" the modelling work in so far that clear goals for the future are articulated and "only" the realisation needs to be investigated.

Sustainable development is a normative concept of intra- and inter-generational justice. Numerous definitions of the concept exist but none can be considered to be *officially endorsed*. A very general meaning of the term was presented in the study *Our Common Future* (also known as the *Brundtland* Report [WCED, 1987]) issued by the World Commission on Environment and Development (WCED), set in place by the UN General Assembly in 1983. The report defines a sustainable development as

"a development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Bearing in mind that future is not limited in any way, this statement implies a certain degree of equilibrium that has to be reached on a global scale. Due to the physical restrictions enforced by the nature (e.g. fossil fuel stocks, climate impacts, solar insolation, ...), the central challenge will be to establish something like a balanced state.

It is obvious that processes related to this global aim operate over decades and centuries. One revealing example is the expected saturation of world population, which will take place, at the earliest, during the second half of the 21st century. So modelling a sustainable energy system and contemplating long term developments are inevitably chained together.

VLEEM is not the first project which deals with the very long term. Well–known studies on this issue include the 2001 IPCC report [IPCC, 2001] and the IIASA–WEC studies (1998) [Nakićenović, 1998]. An outline of the challenge of long term modeling approaches is presented in [VLEEM, 2004].

VLEEM is based on a very different approach in opposite to these earlier studies. A cornerstone of the approach is the use of a backcasting methodology. When considering sustainable energy paths, technological development is only one aspect.

It is also necessary to estimate the contribution of each technology using mixed methods. Therefore a combination of forecasting and backcasting proves necessary (see figure 3.12).

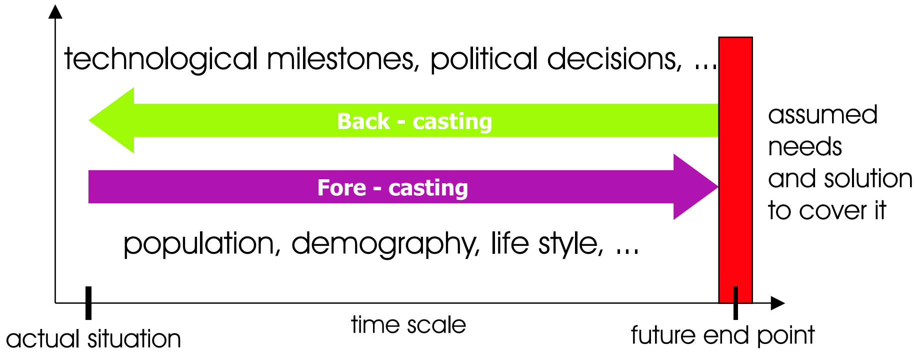


Figure 3.12: *Combination of forecasting and backcasting methodologies to tackle the challenge of long term modelling.*

The proceedure applied to the model approach is as follows:

1. Expected future needs are estimated using a forecasting methodology. The outcome relies completely on the supposed development without restrictions resulting from sustainability criteria or other such limitations.

2. Based on these estimated future needs, an appropriate energy system is proposed. Constraints based on sustainability criteria are placed on this design.

3. Development trajectories are then developed which meet this end-point. These trajectories may also be required to meet additional constraints en-route, to give rise to intermediate or milestone designs.

In contrast to a model treated within the TIMES model generator, the above scheme obtains future development paths that are not enforced by a set of predefined assumptions.

One objective of this thesis is to explore the issue of end-point modelling. The central idea of the end-point is to define an energy system consistent with the sustainability criteria that can be met using technological and organisational measures. Within this context, the design of the end-point is, to a certain extent, arbitrary. As a first step in VLEEM, the end-points are associated with the primary energy carriers. Three different end-points are distinguished:

- *high fossil case*
  Fossil fuels remain the major energy carriers but their carbon dioxide is sequestered to fulfil sustainability criteria.

- *high nuclear case*
  Nuclear power is used to cover all energy needs.

- *high renewables case*
  Renewable energy sources are used in preference to all other options, while acknowledging their upper bound potentials.

The analysis of a possible end-point should give a detailed view of the relation between the various technologies and the primary energy carriers. One purpose, thereby, is to uncover bottlenecks and even infeasibilities. This analysis should help to identify future technological clusters.
With particular regard to the high renewable case, some initial ideas about end-point modelling are treated in chapter 5.

Modelling Methods		
	Forecasting concepts	**Backcasting concepts**
Philosophical View	causality; determinism; context of justification	causality & teleology; partial indeterminacy + context of discovery
Perspective	dominant trends; likely futures; possible marginal adjustments; how to adapt to trends	societal problem in need of solution; desirable futures; scope for human choice; strategy decisions; retain freedom of action;
Approach	extrapolate trends into the future; sensitivity analysis	define interesting futures; analyse consequences, and conditions for these futures to materialise
Methods	various econometric models; techno-economic models	partial & conditional extrapolations highlighting interesting polarities and technological limits;
Techniques	various mathematical algorithms	

Table 3.2: *Forecasting and backcasting concepts according to Dreborg (source* [Dreborg, 1996]).

End-point modelling also requires some explanation of the innovative backcasting approach. The task is to find trajectories able to catch the transformation of existing systems into the desired future system. The preceding discussion does not say why backcasting is needed to tackle this challenge and why the more established forecasting methodology is not as useful. To this end, it is necessary to bring the different concepts to mind (table 3.2), as outlined by Dreborg in 1996 [Dreborg, 1996].

The main reason for using backcasting is to think first about the necessary changes and then about the problems of implementing that change. This thinking is strongly connected with the concept of a sustainable development or more generally with the concept of a desirable future. Hence backcasting and sustainability match well.

Backcasting as applied to the previously mentioned high renewable end-points brings out the development outlined in figure 3.13.

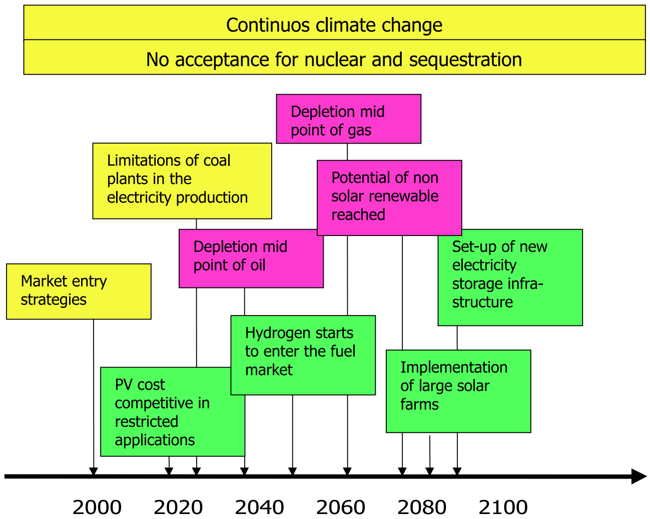


Figure 3.13: *Possible milestones on the way to a high renewables scenario with solar PV being the major energy source.*

After the desired end–point is established, the development is defined by milestones, which smooth the way to reach this aim. The need to defend these milestones presents a major challenge for the backcasting process. These milestones have to fit in the desired development towards a sustainable future and also have to comply with any further limitations which may have been introduced. Their impacts have to be quantified and incorporated in the complete development.

Based on the combination of concepts presented in this chapter, VLEEM sets out to sketch possible paths to a sustainable future. These paths are understood not to be predictions, but rather to represent a range of development options which also acknowledges sustainability criteria.

Chapter 4

Optimisation and simulation tools

The numerical techniques used to model a particular issue are strongly dependent on the stated purpose of the investigation. In this respect, *bottom-up* approaches normally rely on simulation and optimisation methods [van Beck, 1999]. This chapter describes the methods used in the VLEEM project, some of which are novel in their own right.

4.1 Motivation

This thesis is guided by the belief that the model structure selected should be driven by the research issue at hand – and not the other way around. This view also implies that more than one methodology may be required, despite the fact that this will probably increase the modelling effort. More specifically, the choice between simulation and optimisation in their various forms and combinations is a common question for energy modellers. Furthermore, different arrangements can often be used to gain the same result. This thesis attempts to select the best combination of established and leading-edge techniques and to develop new techniques where such an opportunity presents itself.

So the initial intention is to develop a simulation methodology with the capability to represent the behaviour of a system under given fixed conditions. This then allows direct feedback on feasibility of different scenario architectures.
The next step is to establish an optimisation approach on the same hierarchical level. The most common techniques to this end (in passing, also used in TIMES) is linear programming. Although formulating a given problem in linear terms can be challenging. One purpose of this thesis is to establish and implement a more flexible method for optimising a scenario.
This thesis also employs an evolutionary algorithm (EA) for optimisation purposes.

One tremendous advantage of using an EA is that it does not impose as many restrictions on the underlying problem formulation as do conventional techniques, including linear optimisation. Hence part of this thesis is dedicated to new ideas based on EA as implemented in TASES. In addition, the linear optimisation approach provides an opportunity for the comparative evaluation of EA, particularly given the fact that several established models use linear methods.

These established methods also use the *neoclassical* paradigm for their evaluation procedures, so the challenge was also to find and implement evaluation procedures based more on *evolutionary economics*. Extending the experiences made with these unconventional methods presents a future challenge, particularly where more complex multi-agent models are combined with advanced optimisation and (as discussed next) simulation techniques.

4.2 Simulation of energy systems

The term *simulation* warrants a clear meaning. In general, simulation is defined as follows:

Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system and its underlying causes or of evaluating various designs of an artificial system or strategies for the operation of the system [Shannon, 1975].

In the special case of energy systems, that definition encloses the depiction of all the energy flows present. The purpose is, to prove, that the system is able to satisfy a certain demand. The elements of the simulation are energy sources, transformation, distribution, transportation and storage elements. The underlying structure of an energy system has to be mapped to enable the process of modelling. That mapping can, for example, be represented in the manner outlined in figure 4.1.
The idea is therefore, that each process – whether supply, consumption or storage – is described by a heuristic that reproduces the real process behavior in a manner that is sufficient in terms of accuracy and in context of scale of the mapped scenario. In the case of an energy system, an applied heuristic means that the operation mode of each single process is described by a term. In combination with the defined energy system configuration and installation sizes of plant and transmission lines, a simulation covers the operational mode of the entire system.

The modelling emphasis within this thesis is less focused on a detailed technical description of individual processes and more so on the reflection of time and spa-

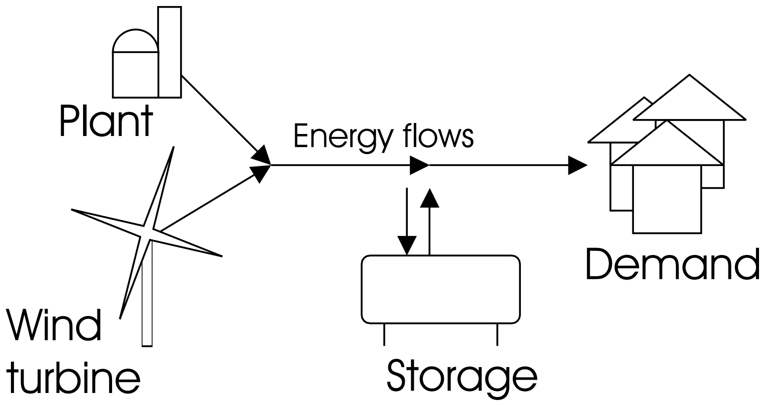


Figure 4.1: *Schematic example of an energy system.*

tially dependent energy flows. To this end, the modelling approach in hand is driven by a heuristic that is implemented in the following manner:

First, a *quality*–factor is assigned to each process. This factor is a function of the specific costs, acceptability, technical availability, and so forth, for the process under consideration. The heuristic, which represents the simulation, collects now all possible paths. The path is defined as all links and processes between an energy demand process and an energy supply process. Each path is signed by a factor defined as the multiplied efficiencies of all participating links and their assigned quality factors. All duly identified paths are collected in a list and then sorted by their combined factor (see figure 4.2).

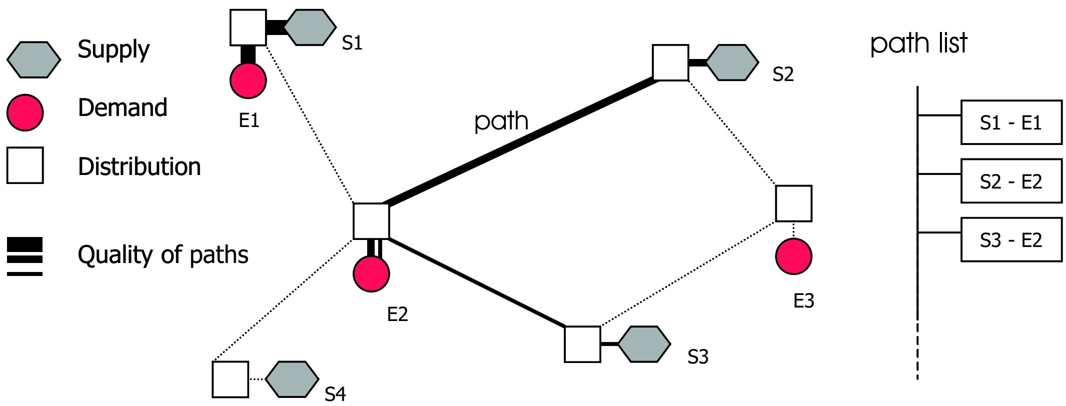


Figure 4.2: *The selection of all possible paths between each pair of termination-points. The paths are collected as a list and then ranked (right hand side).*

After this ranking process, the actual simulation takes place in order to identify the magnitude of the flows. For each time step, an energy balance between supply- and demand patterns is chosen, based on the following heuristic procedure. This heuristic is implemented as follows:

The first ranked – and thereby best – path is used, up to its capacity. This capacity is defined by the weakest link in the path which includes supply and demand characteristics of the two termination-points. In all transmission parts of this path the utilised capacity will be marked to avoid a double utilisation by another path which uses the same transmission slice. Next, the second ranked path is assessed and so on (see figure 4.3) until all demand patterns are covered *or* otherwise the scenario is deemed infeasible.

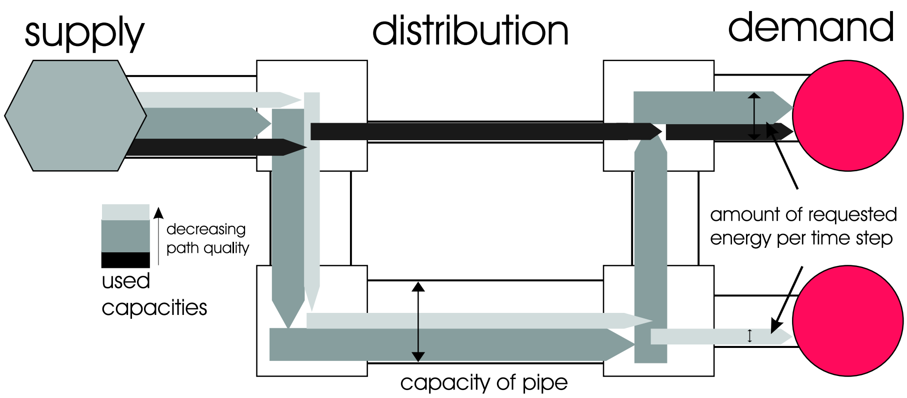


Figure 4.3: *Utilisation of transmission line capacities by executing the sorted path list. The evaluation is repeated for each single time step. Each path capacity is restricted by the weakest participant which includes the associated energy demand and supply capacities.*

The algorithm as implemented is also able to map CHP (Combined Heat and Power) plant and storage requirements. In this case, each CHP node administers two additional path lists, one of which contains all paths to reach electricity consumers and the other which contains all paths to reach heat consumers.
An example is given in figure 4.4. An electricity and an additional heat demand load curve are covered using a CHP plant, a gas turbine, and a simple boiler. The resulting load shares are part of the simulation process.

A storage facility provides two modalities – it can function as supply or as demand. To map a storage facility, the simulation is undertaken twice. In the first pass, a given storage works in supply mode. And in the second pass, this same storage works in demand mode. This has the effect that all uncovered demands use the storage in the first pass, while excess production is used to fill the storage.

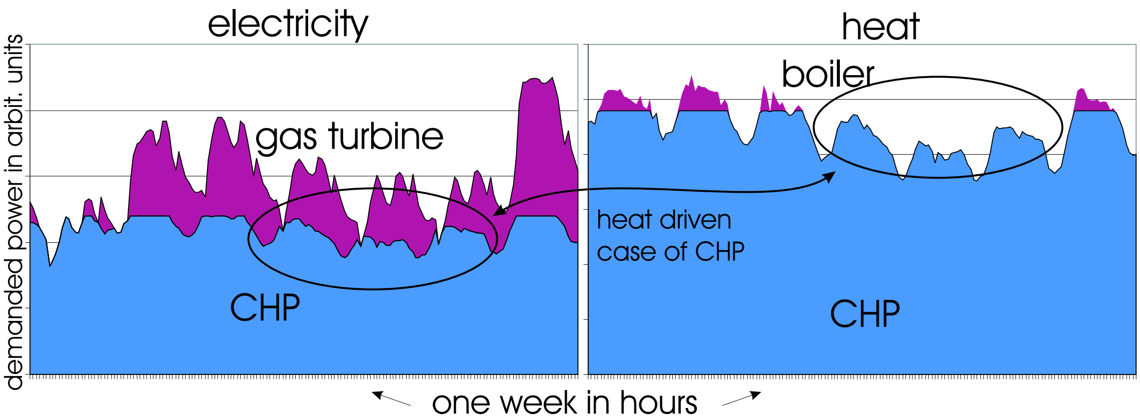


Figure 4.4: *Example showing the treatment of CHP facilities within the simulation process. In addition to details of the installed capacities, the mode of operation also needs to be specified as either heat or electricity driven.*

However, one important difference is that only energy flows which meet or exceed a certain predefined (hardwired) quality threshold are accepted to fill the storage.

Treating a scenario in this way provides an opportunity to identify and record the overall development of the system and each single flow. Therefore, the information collected over the simulated time scale includes data related to all participating processes. This data is available after the completion of a simulation and can be analysed in detail. This represents a major difference with a pure balance model, where only aggregated results are available after the simulation.

One major conclusion from a given simulation is whether the mapped system is feasible or not. All load curves determined for the different processes and commodities are fully dependent on their installed capacities and their assigned *quality*-factors – both of which are simulation inputs.

This ability to act on a given scenario and determine its operational performance is important. But real problems are more complex than this. Real systems also evolve as a result of plant commissioning and decommissioning decisions, changes in consumer preferences, advances in technology, the imposition of new environmental constraints, and institutional change.

Reality is more or less the result of an evolutionary process that leads to certain extent to an optimum state. So what is more obvious than the attempt to describe a system by an optimisation process.

4.3 Optimisation of energy systems

4.3.1 What defines optimisation?

Optimisation is the process of finding the conditions, i.e. the values of variables, that give the minimum (or maximum) of the objective function [Frangopoulos, 2003].

Faced with this definition, the optimisation of a system seems relatively straightforward and indeed, the optimisation process itself, with all its different approaches, is well known and widely published. The real challenge is contained in the aforementioned *objective function*. This function contains all the variables that contribute to the nominated system performance *objective*. In the case of an energy system this *objective* may be defined variously as the aggregated global cost relative to demand or, alternatively, some proxy for reliability, efficiency, or environmental impact. In light of this multitude of potentially conflicting system goals, some resolution is needed.
In energy systems additionally two regions of optimisation can be distinguished [Frangopoulos, 2003]:

- *Design Optimisation.*
  The word *design* is used in this work to imply the technical characteristics (specifications) of the *commodities* and *processes*. The *design optimisation* determines mainly nominal capacities of new installations.

- *Operation Optimisation.*
  For a given system (i.e. one in which the design is fixed) operating under specified conditions, the optimum operating point is sought, as defined by the operating properties of components and substances in use.

So the task of optimisation, as framed above, cannot be defined in a fully global context. The number of constraints and therefore the degree of freedom in the optimisation is highly dependent on the aim to be met. As can be readily imagined, the time effort for solving a problem rises exponentially with increasing problem size – that is, with increasing degrees of freedom and/or computational load.
In this work, each optimisation process arises from the determination of the actual optimum for an objective function under given constraints. The constrained optimisation problem can be formalised as follows [Frangopoulos, 2003]:

$$\text{minimize} f(x) \tag{4.1}$$

with respect to

$$\mathbf{x} = (x_1, x_2, \ldots, x_n) \tag{4.2}$$

subject to the constraints

$$h_i(\mathbf{x}) = 0 \qquad i = 1, 2, \ldots, m \tag{4.3}$$

$$g_j(\mathbf{x}) \leq 0 \qquad j = 1, 2, \ldots, p \tag{4.4}$$

where

$\mathbf{x}$	=	set of all independent variables,
h_i	=	equality constraint functions, which constitute the simulation model of the system,
g_j	=	inequality constraint functions corresponding to design and operation limits.

To handle these various claims, a variety of approaches and mathematical tools can be chosen, of which the evolutionary approach is certainly the most general. In this thesis, therefore, some initial attempts are made in utilising this optimisation strategy for the particular case of dispersed energy systems.

4.3.2 Evolutionary optimisation

4.3.2.1 What is evolutionary optimisation?

Evolutionary optimisation is arguably as old as evolution itself. And biodiversity is the best example of its application. Since Charles Darwin published his landmark theory in 1859 with the *Origin of the Species* [Darwin, 1859], the ideas of evolution have mostly remained with the realms of biological science. Exceptions include social Darwinism and the economic thinking of Schumpeter [Schumpeter, 1962]. But it is only within the last 30 years that these principles have been applied to numerical optimisation.

In the 1970's, two concepts arose – the genetic algorithms (GA's), first developed by J. Holland [Holland, 1973] in the USA and the evolutionary strategies (ES's) principally developed by I. Rechenberg [Rechenberg, 1973] in Germany. A considerable amount of literature (e.g. [Grossmann, 1999]) examines the differences between both methods.
In general, evolution is a process that can be formulated in the following manner:

$$\forall j \in 1 \ldots n \qquad \mathbf{X}_{i+1}^{j} = \mathbf{O}(\mathbf{X}_i^1, \mathbf{X}_i^2, \mathbf{X}_i^3, \ldots, \mathbf{X}_i^n) \tag{4.5}$$

where $\mathbf{X}_i^j$ is the j–th solution in the solution pool at the time step i and $\mathbf{O}()$ is a certain evolution operator.

That means that each single solution at a certain time step is a direct result of the solutions of the previous time step.

The evolution operator itself is based on the principles of biological optimisation. The operation is the combination of the following steps:

- *Mutation*
  targets all processes that can potentially produce a change of a former solution to obtain a new solution,
- *Crossover*
  merges two or more solutions to form one new solution,
- *Selection*
  identifies the surviving solutions.

The optimisation procedure uses an iteration of these steps. And proceeds until the change in the objective function value becomes marginal.

4.3.2.2 Reasons to chose evolutionary optimisation

Relatively few examples of evolutionary optimisation applied to energy systems appear in the literature. See, for example, [González-Monroy, 2002], [Córdoba, 1999], or [Werner, 2000]. One reason for this lack of interest is the sophisticated numerical effort required in order to gain acceptable solutions.

Nevertheless, there are also some very considerable advantages arising from the application of evolutionary approaches in the field of energy system analysis. One self-evident advantage is the more or less complete decoupling of the optimisation process from the underlying complexity of the system. This means that optimisation problem is not driven directly by the system formulation, but by more general considerations. This then enables the examination of very sophisticated systems without losing analytical or numerical tractability. Essentially, very complex systems can be optimised without the need to compromise the system description.
Another property of an evolutionary approach is the independance from predefined deterministic solvers. Therefore under certain circumstances such approaches may fail to converge to a global optimum. Only probabilities can be specified under wich a certain optimal status can be reached.
Compared to that weakness the gained freedom in this solution finding process enables also the implementation of algorithms near to real system evolution. So not only the final solution is of interest, but also the intermediate solutions. The may well contain information about the underlying dynamics of the real system.

4.3.2.3 Special implementation

For the evolutionary optimisation method used in this thesis, only two processes are distinguished: *Mutation* and *Selection*. The complete algorithm is shown in figure 4.5.

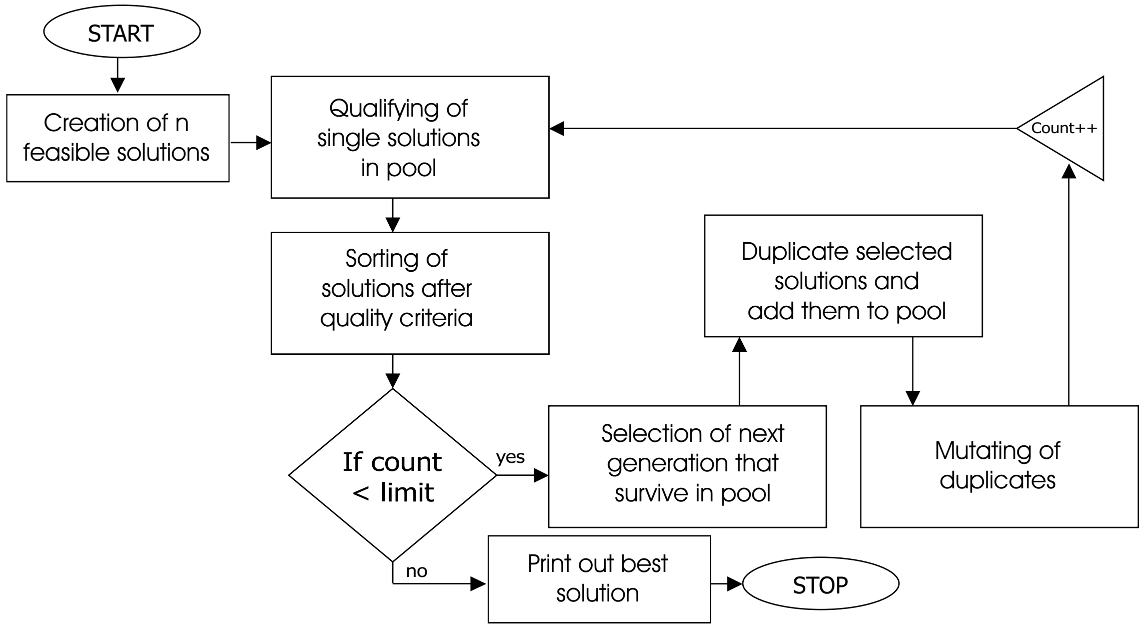


Figure 4.5: *Flowchart showing the algorithm to realise evolutionary optimisation.*

After starting from an initial pool of feasible solutions, a loop of repeating sequences is started which attempts to improve these solutions with regard to a predefined quality criterion (or objective). All solutions in the pool are first assessed and then sorted according to that criterion. Solutions are then selected for survival, based on this ranking and the use of a special selection algorithm. This solution pool then forms the next generation, while the rejected solutions are rejected. To enable the development of higher quality feasible solutions, the surviving solutions are duplicated and these duplicates then mutated. The mutated solutions will again be assessed and ranked. And then placed in competition with the unmodified solutions. With this last step the loop is closed and the process repeated. If the implemented mutation and selection algorithms are well designed, this loop should force the solution pool to stabilise on a state that represents a local or even global optimum. After a fixed number of iterations the procedure is stopped.

Numerous algorithms can be applied to implement evolutionary optimisation, which means primarily the selection and mutation procedures. The following cases can be distinguished:

- procedures which are independent of the special problem to be optimised,
- procedures which reflect special characteristics of the problem to be optimised.

The approach chosen within this thesis follows the second path. This therefore requires additional technical insight. The selection and mutation algorithms are duly conceived using arguments about the behaviour of the real system. This includes a knowledge of issues which affect installation and load attributes of such a system.

There are several ways to identify potentially beneficial mutations, that is variations in the energy system which yield better objective function values. For instance, a variation can be formed by starting from different sides to cause a change on an energy system. Hence the following possibilities can be conceived:

- The variation can take place in the design of a system. This includes the variation of all parameters, that may cause a change to the outward appearance of a system, for instance the enlargement of installations or the rearrangement of process locations.
- The variation can be enforced with regard to the operation of a single process as determined by a heuristic.
- The variation can be directly applied to the load curves of transactions between two location-fixed processes.

In order to choose the most suitable mutation in a system only the available parameters, which can be manipulated without leaving the solution area, need be considered. With reference to the underlying data structure explained in section 2.3.1, the only hard constraints for a given energy scenario are the predefined demand load curves. Moreover, these load curves are attributes of individual demand processes. Therefore each variation, as applied to the system, that does not preclude the satisfaction of a demand curve is admissible and may lead to a better performing system.

The possibility of generating a variation in terms of system design by individual facilities (except fixed demand processes) while freezing operational procedures represents a very interesting approach. This approach can be motivated by a series of reasons and will discussed in more detail in section 4.3.3.
A variation in the operation of a single process may also cause a higher performing system solution. But neither the first nor the second possibility (see the bullet points above) is able to carry out a valid variation on the system alone, which may be flexibel enough to reach all possible system solutions. Only a sophisticated system design variation in combination with the possibility to vary also the intrinsic

operation mode heuristics can be imagined to serve the demanded flexibility.

Therefore it may be of interest to consider the load curves within the system. Each process is defined via the load curves of incoming and outgoing commodities. These streams are all administrated in linkage processes that connect two processes. With this in mind, it is obvious that the complete system is determined by the load curves of the linkage processes, collectively. It is also self-evident, that the load curves themselves are dependent on the installed capacity of independent processes and therefore on the design of the system as well as on different operation modes assigend to individual processes. As a consequence, forcing a variation to load curves can affect both, the system design and the operation mode. To obtain the required level of flexibility for system variations, it must be guaranteed that load curves of processes, not fixed by a direct linked predefined demand, may reach each imaginable form by the applied variation and therefore this approach is evaluated, in comparison with the mentioned alternatives, as the most innovative one.

Due to this mutation strategies implemented, the evolutionary optimisation approach only enforces variations to the system which affect single load curves. One suitable approach that comes up with such an idea will now be discussed in more detail.

First, an initial population of possible solutions needs to be established. This initial population necessarily resides in the solution space. The term *initial population* indicates a set of feasible solutions which are more or less evenly distributed over the complete solution space and are, in general, far away from the optimal solution. In terms of energy systems, the preparation of these initial solutions is undertaken by assigning arbitrary fractions of the consumption load curves, as outlined in figure 4.6, to connected, randomly chosen, paths (see also section 4.2).
Next, each demand structure within the scenario is examined by the mutation algorithms, explained below, until a feasible solution is located. This procedure is repeated n times to generate a pool of n feasible solutions that act as the starting point for the optimisation process.

4.3.2.3.1 MUTATION **of feasible solutions** It should be a property of the mutation process that every possible solution in the solution space is accessible. Despite this, not every possible solution has the same probability to be optimal or be close to optimal. This observation is very important with regard to the performance of the overall optimisation process. Hence, the design of the mutation procedure presents a sophisticated challenge. The other major challenge is to formulate mutated solu-

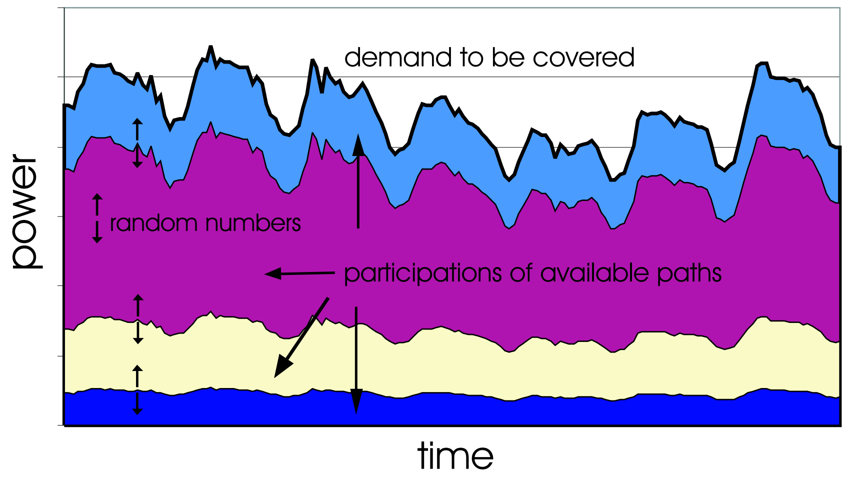


Figure 4.6: *A random partitioning of a consumption load curve in order to assign the slices to connected paths.*

tions which are automatically feasible. If not, the performance of the solver degrades substantially.

Each load curve (representing a link that joins two nodes) can be manipulated as long as the new situation complies with the mandatory constraints – e.g. demand patterns and availability of intermittent sources. As mentioned earlier, considering the set of load curves is sufficient and changes in one curve will naturally impact other curves if they are coupled in some fashion.

The mutation procedure, therefore, acts on one load curve chosen at random, modifies and freezes this curve, and then allows the simulation to find a new equilibrium of load curves. Or, in other words, a new equilibrium of commodity flows. This procedure is indicated in figure 4.7.

One link (in this case marked with 1), leading to a distribution facility (a) or to a storage facility (b) (note that demand nodes can be neglected because the are constraints and hence their directly connected links also) is selected at random and a mutation chosen which alters its load curve. This mutation will be now adjusted with respect to one of its covering paths, also selected at random, up to a root (or source) node and the feasible fraction is applied (discussed in more detail later on). In the case of a *storage* end node, a new equilibrium is simply set because compensation can be handed over to another time range in the load curve and need not yield in the actual considered time range. In the case that the starting point is a *distribution* node, a new balance has to be established through simulation. This will be realised by selecting another path at random (marked with 2) but which also reaches the *distribution* node under consideration in order to compensate for the previous variation. This procedure facilitates the exploitation of the spatial dimen-

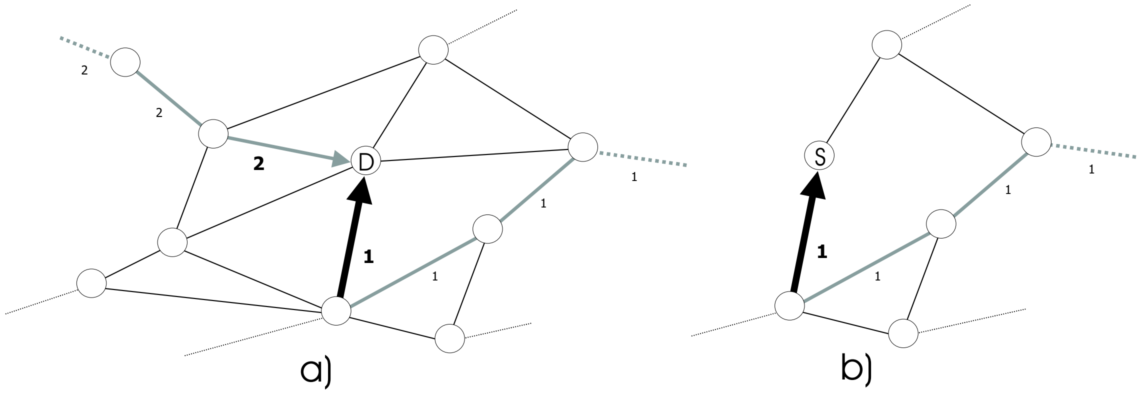


Figure 4.7: *A new solution is generated by forcing a mutation to one randomly chosen path ending at a distribution node that is compensated via another randomly chosen path ending at the same node (a), or to one randomly chosen path ending at a storage node (b).*

sions within the solution space.

It can be readily seen that the number of possible solutions explodes due to the high dimensionality if the solution space of the mapped scenario increases in only one of this dimensions. In order to handle this rapidly increasingly solution space, the more reasonable solutions must be assigned a higher probability of selection. This can be done by using an intelligent path electing algorithm and an intelligent load curve mutation process. Choosing more probable paths is strongly dependent on scenario patterns and is unlikely to be solved using hardcoded algorithms. A more suitable approach requires the use of custom mutations. Therefore a consideration of the inductive constraints may be useful. These are the fixed demand patterns on one side and the supply patterns on the other side. Crudely categorised, these supply techniques can be divided in three groups:

- ***base load plant***
  slow response plant with high investment and low operation costs. Such plant are often used to cover the permanent part in the demand pattern (e.g. nuclear power stations).

- ***peak load plant***
  fast response plant with low investment and high operations costs. These are used to cover the volatile part in the demand pattern (e.g. gas turbines, hydro-dams)

- ***highly intermittent renewable plant***
  a range of technologies with a highly fluctuating (but not necessarily unpre-

dictable) offer characteristic (e.g. photovoltaics, wind turbines). The incoming streams are often unpriced but investment costs are high. Normally the aim is to dispatch these plant first.

These insights mean it makes sense for the mutation procedure to focus on particular load curves related to classification. Therefore the mutation process is split in several independent actions. One mutation function is responsible for finding a rough distribution of the reasonable energy supply, as outlined in figure 4.8.

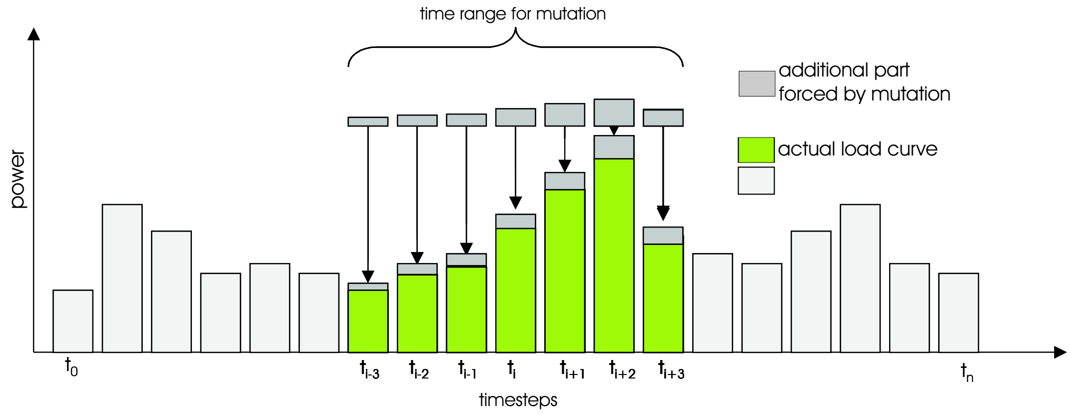


Figure 4.8: *A slice from a set of load curves is mutated by multiplying a randomly chosen, but for the complete time range, consistent percentage value.*

From a randomly chosen time range (set of time steps), but one with certain higher probability relative to the complete time horizon, an arbitrary fraction of the load curve is picked and a percentage value is multiplied. This procedure allows a very rough tuning of the energy flows taking place. The fact that the time slice and the percentage value are chosen arbitrarily helps to guarantee that all possible solutions are accessible through mutation. Nevertheless it is not really suitable to present the special behaviour of the mentioned base- and peak load facilities. To force this special behaviour – especially with regard to the distinction between base and peak load – another mutation procedure is invoked. In this second procedure, the base load shares will be divided by peak load shares, by cutting an arbitrary slice out of the load curve using a randomly chosen time range (as indicated in figure 4.9).
The two mutation procedures just described cover all the possibilities for finding a balance for direct energy flows, that is those flows not associated with storages. However these two procedures alone are not suitable for fixing the characteristics of any storage technologies present. The input stream in a storage process acts as *demand*, but one which cannot be predetermined. Up to this point, only known demand curves have been admissible. But the input streams for storage processes are not known from the beginning. A storage can be accommodated by adding a

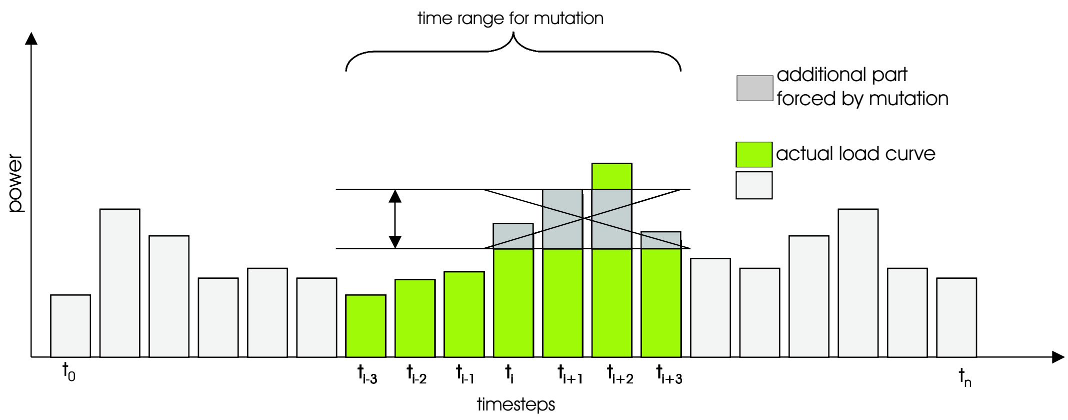


Figure 4.9: *An arbitrarily chosen band from either a complete load curve or only one slice is removed in order to conduct a mutation to the system.*

constant load value to the previously identified time range data and then allowing mutations to act on the incoming links. This constant load value is arbitrarily set using the load range of the assigned outgoing links.

In summary, the three mutation procedures allow the optimisation approach to reach an optimal state but nevertheless a further procedure is necessary to guarantee that the complete solution space can be covered with an acceptable probability. A fourth and final mutation procedure, responsible for reaching every solution in the solution space, allowing the individual mutation of each single time step (shown in figure 4.10) closes this gap.

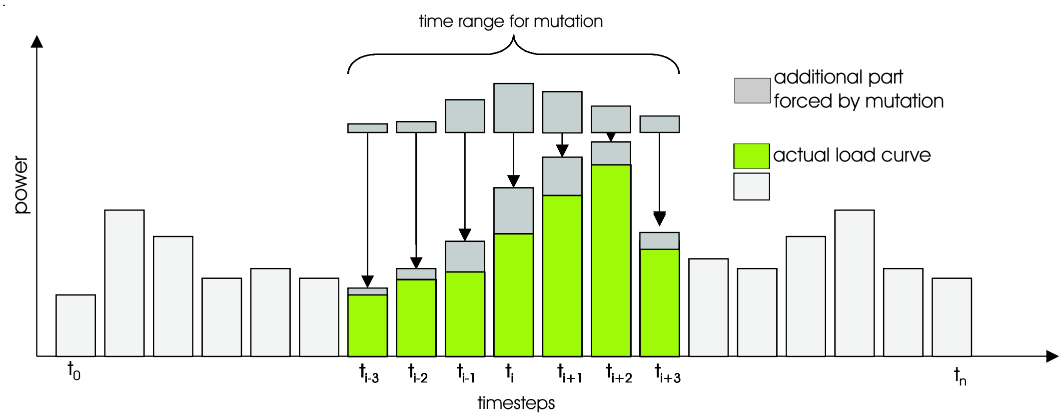


Figure 4.10: *A Mutation is forced to a randomly chosen slice out of a load curve by multiplying a percentage value to this slice that is peaking in the middle.*

For a randomly chosen time step t, the load curve value can be changed (increased or decreased) by an arbitrary chosen factor. To make this mutation more realistic, the neighbouring (regarding the time step) load values – located in an arbitrary chosen surrounding range – are also shifted randomly, but in a range that is limited by the mutation value of the enclosed time step. In general, for a randomly chosen time range, an arbitrary fraction of the load curve is elected and a percentage value is multiplied that falls to zero at the borders of the time slice.

After settling on a suitable mutation, the next stage is to force this modification on a randomly chosen path up to its root node (as mentioned before). Forcing this modification means that constraints given by the solution space must be acknowledged. In the current case, no load curve may become negative (noting that all flows are directed). Reaching the root adds the further challenge of finding an acceptable compromise between the asserted modification and the characteristic of the root node.

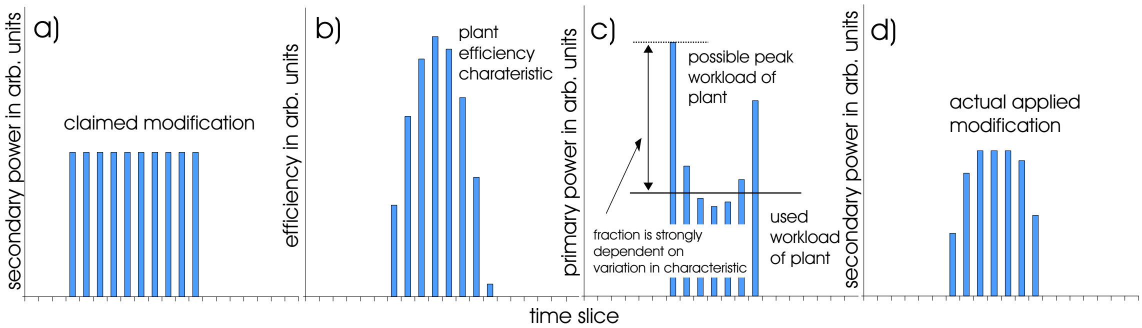


Figure 4.11: *A load curve modification (a) that is requested to be satisfied by a plant with an enforced efficiency characteristic (b) (e.g. solar plant) presumes a primary installation (c) that will be limited with a certain probability to a reasonable value and leads therefore to an actually accepted modification (d).*

For instance, it may not be possible for the root node to oblige, say in the case of photovoltaic installation. Therefore the actual capabilities of the root are examined and depending on the variation in the requested duty, a fixed fraction of the peak capacitity is chosen to satisfy the actual modification as accepted (compare figure 4.11).
This collection of mutation procedures provides, in combination, a good compromise between the high flexibility and reasonable solutions.
The details of the mutation algorithm are summarised in figure 4.12. Starting with the selection of one link, a random process also determines which mutation procedure will be applied to the load curve of this link. A feasible part of this mutation is applied upstream back to a root node by exerting the algorithms out of the simulation tool, as already discussed. The inverse of this feasible part will next be applied

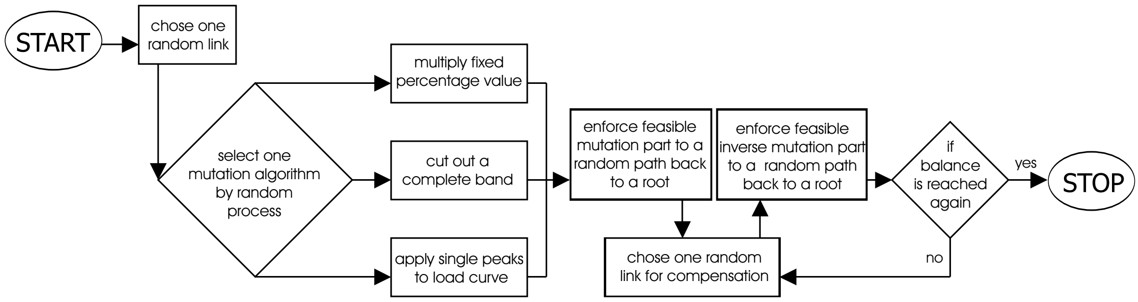


Figure 4.12: *Flowchart for the mutation algorithm which is used to determine mutated feasible system solutions.*

to another randomly chosen path which is able to compensate for this earlier variation. This last procedure is then repeated until the original variation is completely compensated for in terms of system balance to yield a new feasible system solution.

After the mutation algorithm is complete, a sophisticated election or ranking procedure is applied in order to find a suitable parent generation for the next stage of evolution.

4.3.2.3.2 Selection **of next parent generation** In the next stage a new parent generation is selected. The first issue is the quality of a given solution. This quality is represented by the so-called *quality value* as determined by the objective function. The role of this objective function is to translate all of the characteristics of a solution into an accompanied *quality values.* Here the *quality value* is based on real investment (fixed) and operation (variable) costs and a *penalty* cost when a given solution departs from some definition of reasonable or even feasible.

All solutions of the current solution pool are quantified with their *quality value.* The selection of the next generation is done by a two step process.
The first procedure is a simple one. Each *parent* solution is compared with its direct *child* solution. In the case where the child solution is "cheaper" based on its *quality value*, the two solutions are swapped in every case. Otherwise, the two solutions are only swapped with a probability $p = exp(-\Delta H/T)$ (compare [González-Monroy, 2002]). Here ΔH is the variation of the *child cost value* (H_c) to the *parent cost value* (H_p) and T is the maximum range of allowed modifications in the mutation process. Formally this procedure can be stated as follows:

- $\Delta H \leq 0 \rightarrow$ swap with probability $p = 1$,
- $\Delta H > 0 \rightarrow$ swap with probability $p = exp(-\Delta H/T)$,

where $\Delta H = \frac{H_c - H_p}{<H>}$;

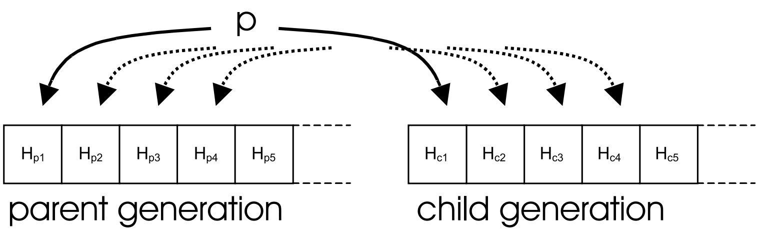


Figure 4.13: *Each parent solution is swapped with its direct child solution based on the value of probability p.*

Figure 4.13 shows this functionality. This election process guarantees that every root *parent solution* is represented in the next generation by itself or by its child. It is necessary to ensure sufficient diversity in the solution pool in order to avoid an early stalling of the evolution process at a suboptimal state in the sense of reaching a poorly performing local optimum.

Nevertheless, it is also necessary to allow the extinction of single solution families in order to free space for the advancement of better performing solution families. Therefore an additional selection procedure is required, as outlined in figure 4.14.

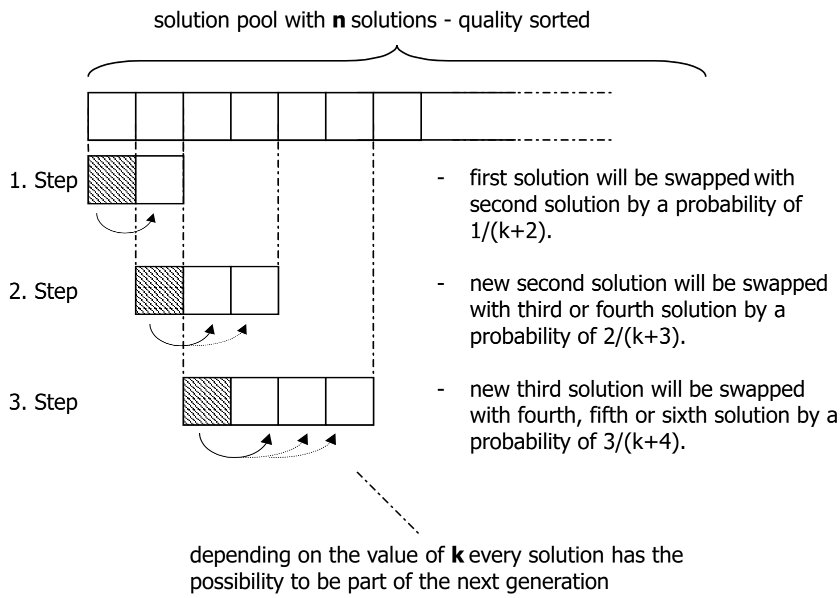


Figure 4.14: *Algorithm which selects the solutions which survive to the next generation from a list of sorted solutions.*

This new selection procedure first sorts all solutions based on their *quality criteria.* It then selects from the solution pool comprising n solutions, a new parent generation with $n/2$ solutions, by applying the following sequence:

- The first (and therefore best) solution is swapped with the second solution with the probability is $p = 1/(2+k)$.
- The new second solution is swapped with the third or fourth solution with the probability is $p = 2/(3+k)$
- The third solution is swapped with the fourth, fifth, or sixth solution with the probability is $p = 3/(4+k)$
- etc. ...

The process is finalised after reaching the $n/2^{th}$ step and the new parent generation is now represented by the first $n/2$ solutions in the pool. These can be readily retraced – each solution in the pool has a probability $\neq 0$ (strongly dependent on $k \in \mathbf{N}_0$) to be part of this generation.

A slower acting but more harmonious selection procedure can also be formulated, based on the Fermi–Dirac–statistics. In this arrangement, the quality criteria of the single solution is interpreted as a quantum energy level and the solution indicated by $n/2$ represents the "Fermi"–level.

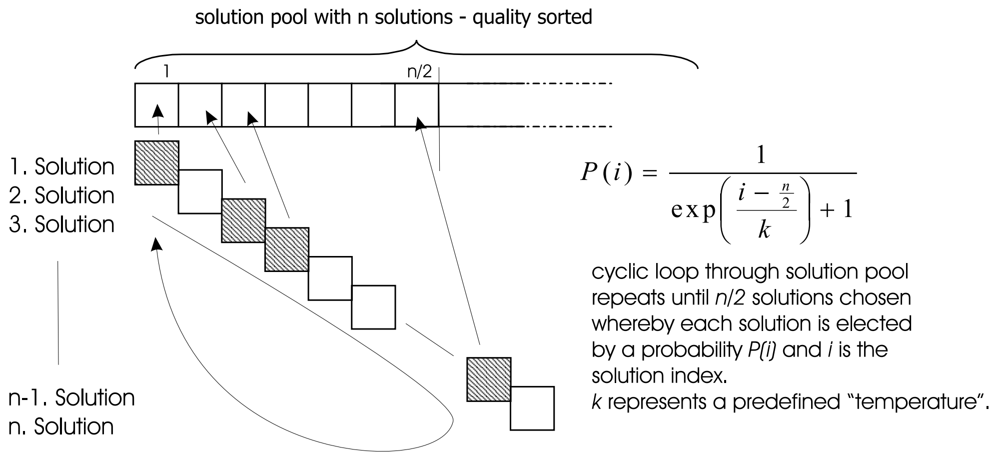


Figure 4.15: *An algorithm to select solutions which are to survive to the next generation from a list of sorted solutions based on Fermi–Dirac–statistic.*

The algorithm outlined in figure 4.15 guarantees that each solution in the pool survives with a probability corresponding to its quality index (energy level). Therefore a cyclic loop acts on the solutions in the pool and elects each solution with an assigned probability as surviving. This is repeated until $n/2$ solutions are classed as surviving. The parameter k acts, in this case, as a "temperature" which smooths the sharp transition at the "Fermi"–level.

Both selection algorithms reveal their own performance statistic due to the value of k. In figure 4.16 this behaviour is outlined.

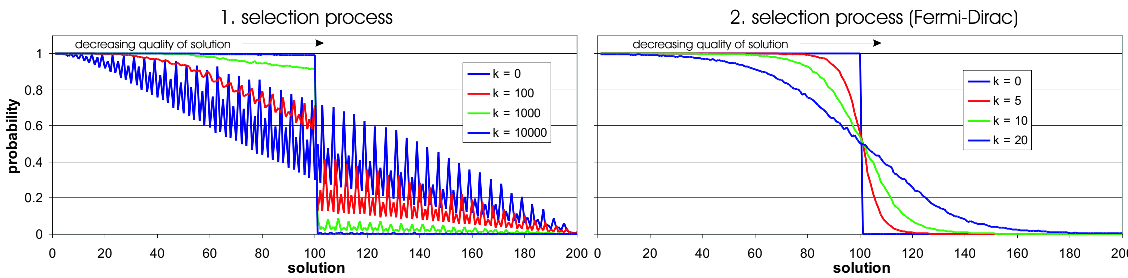


Figure 4.16: *Performance statistics of the two selection algorithms operating on a pool with 200 solutions. The survival probability based on an evaluation of 10000 runs is shown. For each solution, the survival probability is dependent on the predefined value of k as indicated.*

The first selection algorithm shows a periodic structure in the probabilities for solutions of one following the other. In highly complex problems that deficiency can be overcome by using the second selection algorithm. The probabilities in this latter case are strictly determined by the Fermi–Dirac statistic.

The optimisation itself is realised by applying a sophisticated sequence of the *mutation*- and *selection* procedures described above. The effects on the actual sequence will be explained in more detail in section 4.3.2.5.

4.3.2.4 Applied example

The strength of this kind of optimisation lies in the more or less complete freedom with respect to scenario simulation. This optimisation strategy is completely decoupled from the underlying mathematical description of the problem under investigation, in marked contrast to conventional optimisation approaches. As a consequence, even highly complex scenario patterns may be optimised without the need to accept the kind of restriction required by other approaches.
To conclude this topic, a simple example is given. The example draws the special emphasis in this topic concerning this high complexity (see figure 4.17).
One predefined electricity demand is to be covered by a conventional plant with additional storage ability to smooth mismatches in time between offered and requested

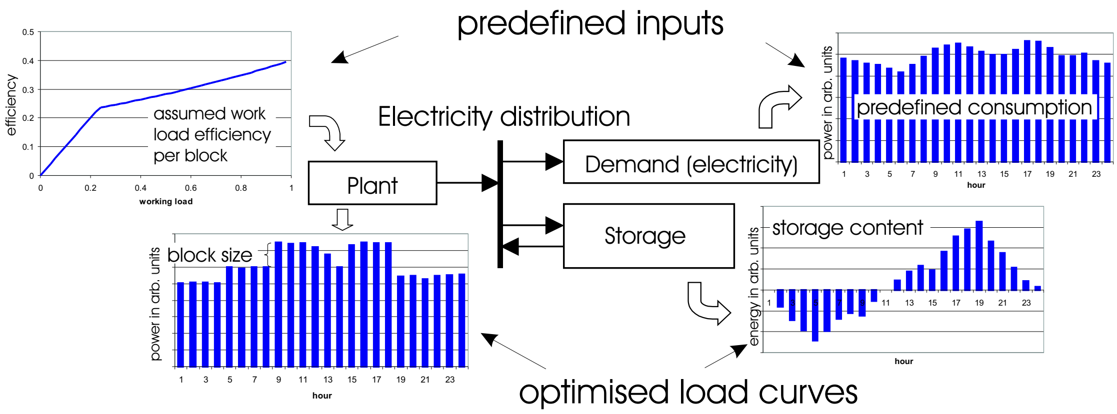


Figure 4.17: *A non–linear optimisation example optimised using an evolutionary approach. The goal is to find the hypothetical plant behaviour.*

electricity. The plant can only be installed in discrete block sizes and these blocks show an efficiency profile that is strongly dependent on their selected duty. Such efficiency characteristics are normally a challenge for conventional optimisation and can only be handled with extra effort.

Regarding the high flexibility of the method concerning simulation or optimisation topics that can be treated with an evolutionary access. Tackling such complex scenario relations is one of the major abilities of an evolutionary approach.

4.3.2.5 Performance appraisal

All the mentioned optimisation approaches have their own strengths and weakness. It makes sense, therefore, to review the performance of each, even when the methods are non-deterministic, as in the case of the evolutionary approach.

In this latter case, the context is significant and various predefined parameters can impact on the success of an optimisation run:

- What range for mutations are accepted?
- Which mutations at what stage are useful?
- What sequence is useful between mutations and selections?
- What selection process at what stage is useful?

At this point, a general overview of possible developments within the solution pool are of interest. These developments can be visualised by a two-dimensional array, as shown in figure 4.18.

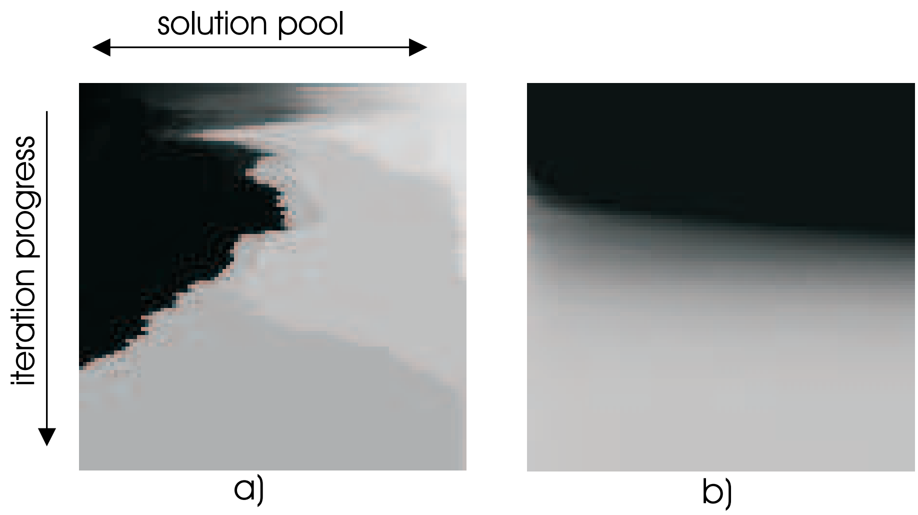


Figure 4.18: *Development in an optimisation run: (a) each gray value represents one family; (b) each gray value represents the assigned quality level of the underlying solution (pale means solution is near to global optimum).*

The horizontal axis represents the actual solutions in the pool with each initial solution – visualised by its own gray value – represents one *family* (figure 4.18 a). The vertical axis indicates the progress in evolution. Each periodically repeating sequence of *mutations* and *selections* (full iteration) leads to an alteration of the pool as indicated in the graphic 4.18 by representing the actually available *families.* It is readily apparent which *family* dominates at the end of the iteration and this *familiy* is expected to point to the optimal solution. The second graphic (figure 4.18 b) shows the same optimisation run represented by the single solutions, not coded by their relation to one family, but by their relative *quality* with respect to the optimal solution (light gray indicates good relative quality).

To increase the rate of reaching the optimal solution, a certain level of diversity within the solution pool must be guaranteed – so to speak, the numbers of participating families has to be held high until one can be selected as the overall favorite. After reaching this state – through what is surely a smooth transition – the solution pool can then be populated by the children of this favoured solution in order to focus further effort on seeking the optimum.

Two limit boundaries can be constituted (shown in figure 4.19) that may well have a negative impact on performance.

The first possible case (indicated in 4.19 a) is that one family dominates the solution pool at an early stage. This leads – given that this family is not near to the optimum

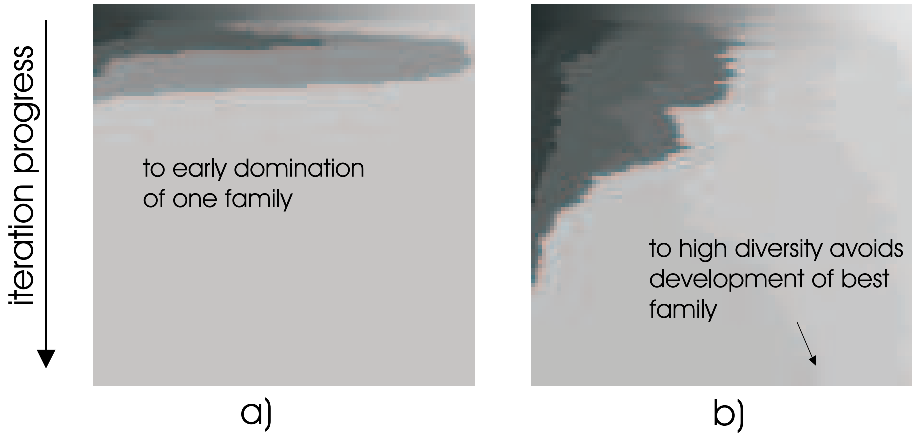


Figure 4.19: *Two possible shortcomings in the evolution pool and its development may be: (a) too keen a selection criteria, and (b) too lazy a selection criteria.*

as generally implied – to an early loss of diversity. This again can result in a decreased rate of progress and perhaps complete stalling of the system at a local optimum because mutations occupy a subregion of the solution space.

The second possible case is that the selection process is too indiscriminate (sloppy) so that no family – neither the best endowed – gets the chance to dominate the pool (figure 4.19 b).

Fixing the best solution trajectory – meaning, in this context, the calibration of the mutation and selection algorithms – is a challenge that can only be solved empirically. The idea therefore is that mutations must enable neighbouring families to intersect rapidly in order to avoid one family dominating the entire pool by piling its children into an underperforming region of the solution space before other families have the opportunity to succeed elsewhere. This situation can be affected through an alternation of parent – child *swaps* (the aforementioned selection procedure that holds a family in the pool) and one of the complete pool including selection procedures.

However family dominance (piling) is desirable after the pool has had the change to range over the complete solution space and convergence on one evolutionary successful family is now appropriate. At this stage, all activities (*mutation* and *selection*) should guarantee that convergence on an optimum is achieved. This can be enacted by decreasing the mutation size.

4.3.3 Pure energy system design optimisation

One interesting derivative application of evolutionary optimisation is the combination of the aforementioned evolutionary processes and the heuristic applied in chapter 4.2. This idea is bipartite. *Design optimisation* (section 4.3) is undertaken by evolutionary optimisation (above) and *operational optimisation* is conducted by the fixed simulation heuristic (section 4.2).

This two–tier scheme admittedly combines the shortcomings discussed in the previous section, but nevertheless may offer advantages which should not be overlooked. This two–tier approach no longer allows the complete solution space to be traversed, but, depending on the chosen operational mode heuristics, an acceptable *suboptimal* solution can be reached. Aside from the fact that this scheme may be, under certain circumstances, numerically faster than true optimisation, it also, quite possibly, mimics real world decision processes better. So in summary, this two-tier scheme can represent an excellent compromise.

The algorithm sequence for this scheme is the same as with pure optimisation and is explained in figure 4.5. The sole difference is found in the mutation process.

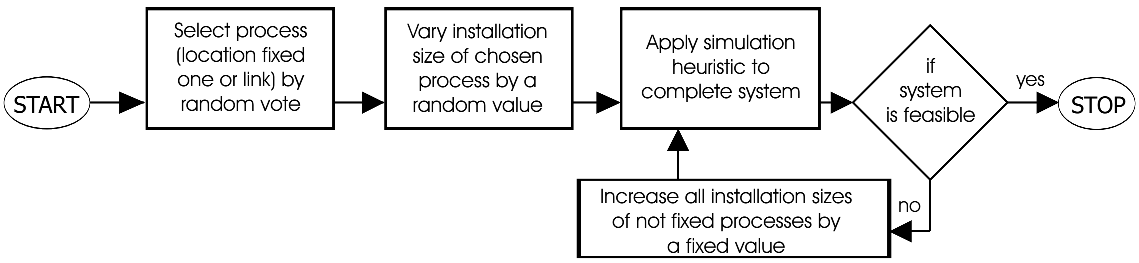


Figure 4.20: *Flowchart showing a mutation restricted to the system design.*

The sequence for this revised mutation process is outlined in figure 4.20. One randomly chosen process will be randomly varied within a predefined range. The simulation heuristic explained in section 4.2 is now applied to this altered system. If this system is found feasible, the mutation is accepted. If the mutated system is found infeasible (that is, global demand can no longer be covered) all processes not fixed will be expanded by a fixed value and the simulation heuristic will be applied again. This sequence is repeated until the system becomes feasible. Even if this may not lead to a better rated solution it avoids that solution space is left.

Due to the fact that progress within the optimisation is dependent on the *randomly* applied *mutations* and *selections* the algorithm provides *no deterministic* finalisation. If a less indeterminate approach is required, then some other optimisation method is required. One established approach with the guarantee on convergence is linear optimisation.

4.3.4 Linear optimisation

Linear optimisation (also known as linear programming) is well known and reliable. To use a linear approach for optimising an energy system requires linear relations for all system equations, constraint equations, as well as for the objective function. All relations have to be formulated and simplified to the form:

$$f(\mathbf{x}) = a + c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{4.6}$$

where $\mathbf{x} = \{x_1, x_2, \ldots, x_n\}$ represents the vector variables.

Nevertheless this approach is very often used in modelling and optimisation issues. A huge number of variables can be handled in an acceptable time scale and for that reason, the approach is considered as a good compromise (see MARKAL, TIMES, etc.).
A simple example for the purposes of illustration is formulated on the following problem [Hu, 2003]:

$$\begin{aligned}
\min \wedge \max f(\mathbf{x}) &= 5x_1 + 4x_2 \quad \text{(objectiv function)} && (4.7)\\
6x_1 + 4x_2 + x_3 &= 24 \qquad \text{(constraints)} && (4.8)\\
x_1 + 2x_2 + x_4 &= 6 && (4.9)\\
-x_1 + x_2 + x_5 &= 1 && (4.10)\\
x_2 + x_6 &= 2 && (4.11)\\
x_j &> 0 \qquad j = 1,2,3,4,5,6 && (4.12)
\end{aligned}$$

Graphically this problem can be visualised as shown in figure 4.21. The constraints collectively mark the possible solution area which is projected in the picture in the (x_1, x_2)–plane. From this solution area, the best solution – with regard to the stated objective function – must now be found. Two different types of methods can be used: the *simplex method* and the *interior point method*.

The simplex algorithm is the most widely-used method for solving such problems. Simplex is based on a known property of linear problems that the optimal solution is always located on a corner point of the solution space. The algorithm, in its simplest form, starts with an arbitrary corner point and checks whether one of its neighboring corner points is nearer to optimal. If so, this better solution is chosen

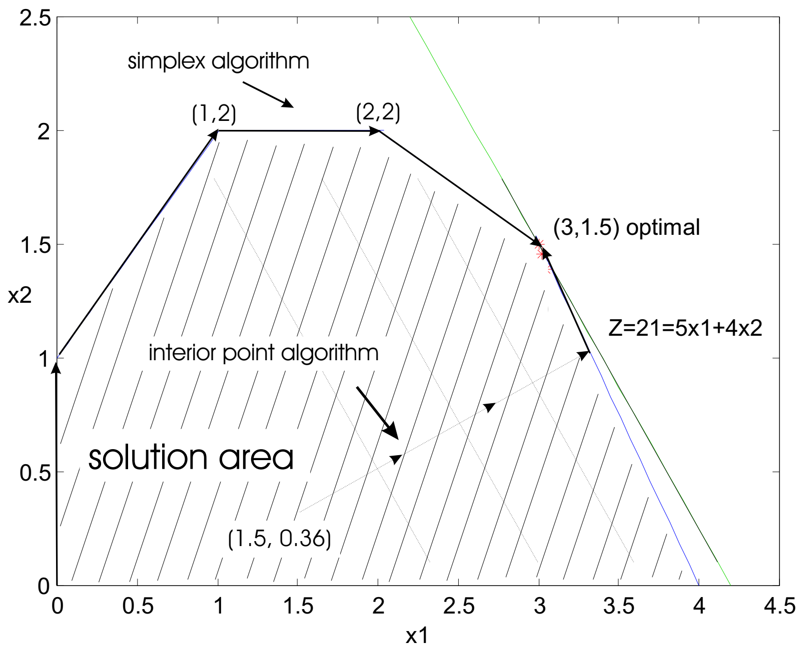


Figure 4.21: *Illustrative linear problem solved using the simplex algorithm and an interior point method. The solution trajectories are marked and these started from* $(0, 0)$ *and* $(1.5, 1.36)$ *respectively.*

and the procedure repeats until no higher performing corner points are accessible – meaning the optimum is reached.

Another approach is adopted by the interior point method. In this case, an arbitrary solution *inside* the solution space is chosen as the starting point. Then the gradient of the objective function is computed numerically and added (Newton method) and the result projected back onto the solution region. This new solution is automatically nearer to the optimum (because the problem is linear). The procedure repeats until the border of solution space is reached and the simplex algorithm is applied for further progress.
The question of which method to employ is strongly dependent on the attributes of the problem to be optimised. A comparison of both methods is given in table 4.1.
Two advanced commercial solvers which support both methods are CPLEX[1] and MOSEK[2] Both products were utilised in this thesis. And both products can handle problems with several million variables and a similar number of constraint equations.

[1]More information available under: www.cplex.com
[2]More information available under: www.mosek.com

Linear optimisation methods		
	Simplex method	**Interior-point method**
Trial solutions	CPF (Corner Point Feasible) solutions	Interior points (points inside the boundary of the feasible region)
Complexity	worst case: # iterations can increase exponentially in the number of variables n: 2^n	Polynomial time

Table 4.1: *Comparison between the simplex method and the interior point method* [Hu, 2003].

In relation to the optimisation problems in this thesis, experience shows that the interior point method performed better. This can be visualised by considering the highly partitioned solution space. There is likely to be at least a localised structure within the solution space, in the sense that many (but not all) improvements are incremental. The interior point method will naturally support this incremental structure, whereas the simplex method tends not to. This is because the interior point method can follow gradient whereas the simplex method is restricted to corner points. So in the case of the simplex method an unfavourable starting point can cause a weak performance because quite a number of unreasonable solutions will need to be visited. That is, why the interior point method is more favourable with regard to the issues at hand.

4.3.4.1 Application to problems at hand

Formulating a problem in a linear manner in order to be able to solve it without difficulty, sounds relatively easy but nevertheless that can represent a real challenge. This is due to the fact that each single constraint or relationship must be captured with a dedicated equation. Therefore, the complete time and spatial resolution needs to be represented by the linear formulation. The method is explained now in more detail shortly.
The actual mapping approach with individual fixed location nodes and connecting links requires the consideration of all time and spatial relationships. Overall, the following equation types (also compare with the aforementioned linear example) can be distinguished:

- OBJECTIVE FUNCTION
  This single equation contains the objective-determined (or decision) variables together with their associated coefficients (e.g. specific costs).

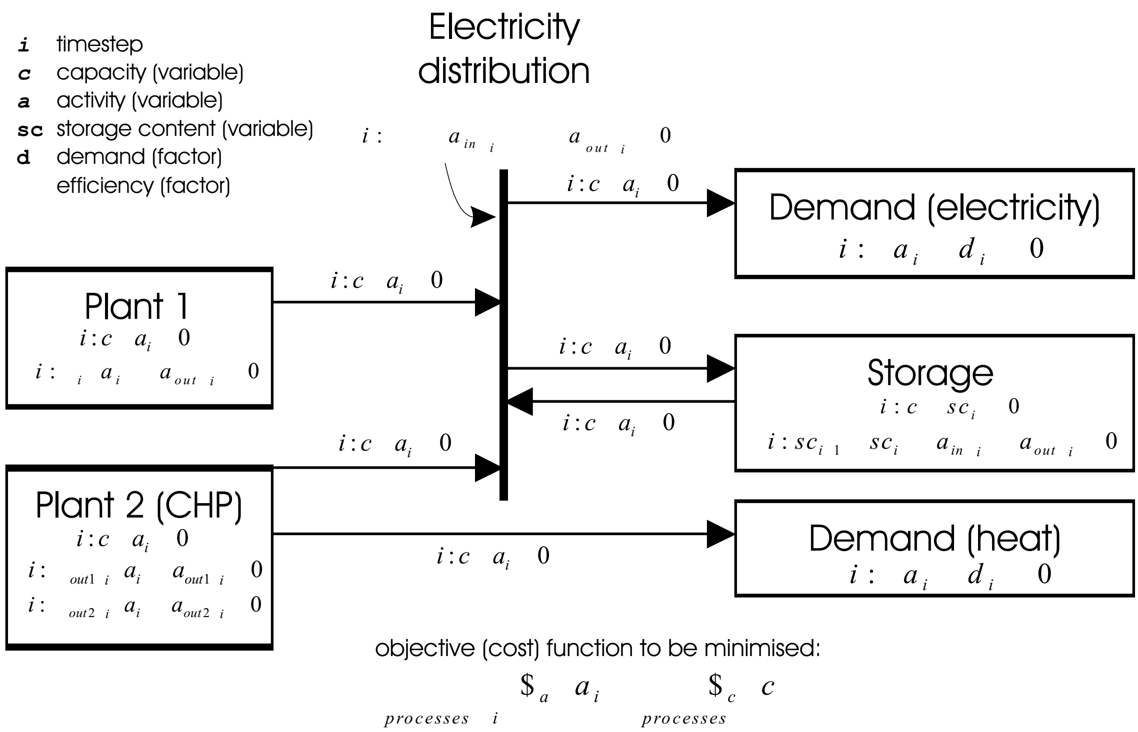


Figure 4.22: *Example of a representative model, described by linear equations. Once formulated in this way, a given scenario can be optimised in relation to the objective function depicted.*

- CAPACITY EQUATION
  Equations specific to each process (be they node or link based) and time step, which carry information about their installed capacity. Furthermore, each flow and stock has its own capacity equation.

- BALANCE EQUATION
  Equations specific to distribution process and each time step which carry information about the relationship between incoming and outgoing flows.

- COM_BALANCE EQUATION
  Equations for each conversion process and any related commodities and for each time step which carry information about the selected duty of that entity.

- STORAGE EQUATION
  Equations for each storage process which contain information about the storage content (inventory). These are normally structured such that storage content in time step t_i plus incoming stream in t_i minus outgoing stream in t_i is equal storage content in t_{i+1} (modeled time horizon is cyclically closed).

- DEMAND EQUATION
  Equations for each demand process and time step that contains information about the incoming stream needed to satisfy the associated demand.

Figure 4.22 shows a representative model which uses these various equation types. The state of each individual process at each time step can be described by just a few variables. The state of the complete system is simply the total (union) of all individual process states.

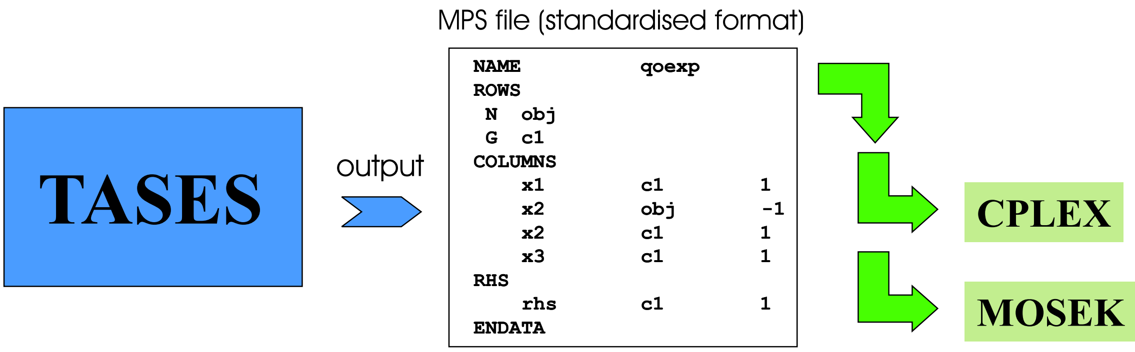


Figure 4.23: *The problem is formulated in the standardised MPS format and then passed to an external solver.*

All the optimisation problem equations are collected and reformulated using a MPS matrix format. MPS is a very common data exchange standard for linear (and related) problems (figure 4.23). Once outlined in this manner, the problem can be passed to a number of third-party solvers for solution.

A huge range of real world questions can be solved by formulating the problem in linear terms. But clearly not all. In fact, most real world examples, from say economics or the social sciences, are not linear. These problems are typically highly complex. On occasion, parts of these system can be satisfactorily mapped to linear models as an approximation. But often problems can only described by more complex relationships.
To solve such complex problems requires a tremendous effort if conventional algorithms are used. To circumvent this effort, one approach is to go back to the heart of optimisation theory and employ evolutionary based approaches.

4.3.5 Contemplation of an illustrative example

In this section, the various aforementioned optimisation approaches are considered by way of an illustrative example (figure 4.24) and then compared. This exercise provides, more or less, a cross section through the capabilities of TASES.

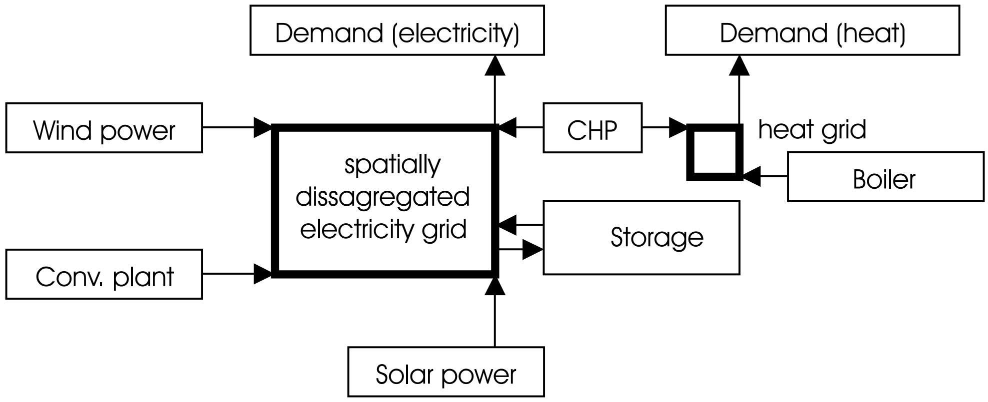


Figure 4.24: *Schematic of an illustrative scenario used to compare and contrast the various optimisation approaches under discussion.*

The example combines, in a small distribution net, intermittent sources like solar and wind power as well as CHP and a storage facility. Each grid also has backup facilities which also compete for use, but are normally dispatched last. All relationships are forced to be linear, to facilitate the direct comparison between the different linear and evolutionary optimisation approaches under consideration. In addition to the load balances between the various sinks and sources, the spatially-driven impacts arising from the grid are also considered.

This particular scenario arrangement is designed to show the suitability of the evolutionary optimisation approach developed in this thesis in relation to the other methods under discussion (figure 4.24). More specifically, this then enables a direct comparison between the different optimisation approaches implemented in TASES. The results of this exercise are shown on figure 4.25. This figure contains the load curves for each process and for each of the different optimisation approaches.

Due to the fact that the linear optimisation method employed is deterministic structured to yield a global optimum on the given scenario, the solution gained by this approach acts as a reference or benchmark. The various cost coefficients, also present in the objective function, were selected such that the scenario utilised all the technologies present. This scenario represents a *worst case* in the sense that all technologies are forced to participate, relative to their individual characteristics, to a system-wide optimal state.

The quality of the nondeterministic evolutionary optimisation algorithm can be evaluated under these less than favourable conditions. Because it is under these conditions that adverse interactions between plant are likely to emerge.

Therefore the load curves could be interpreted as the practicable approach towards

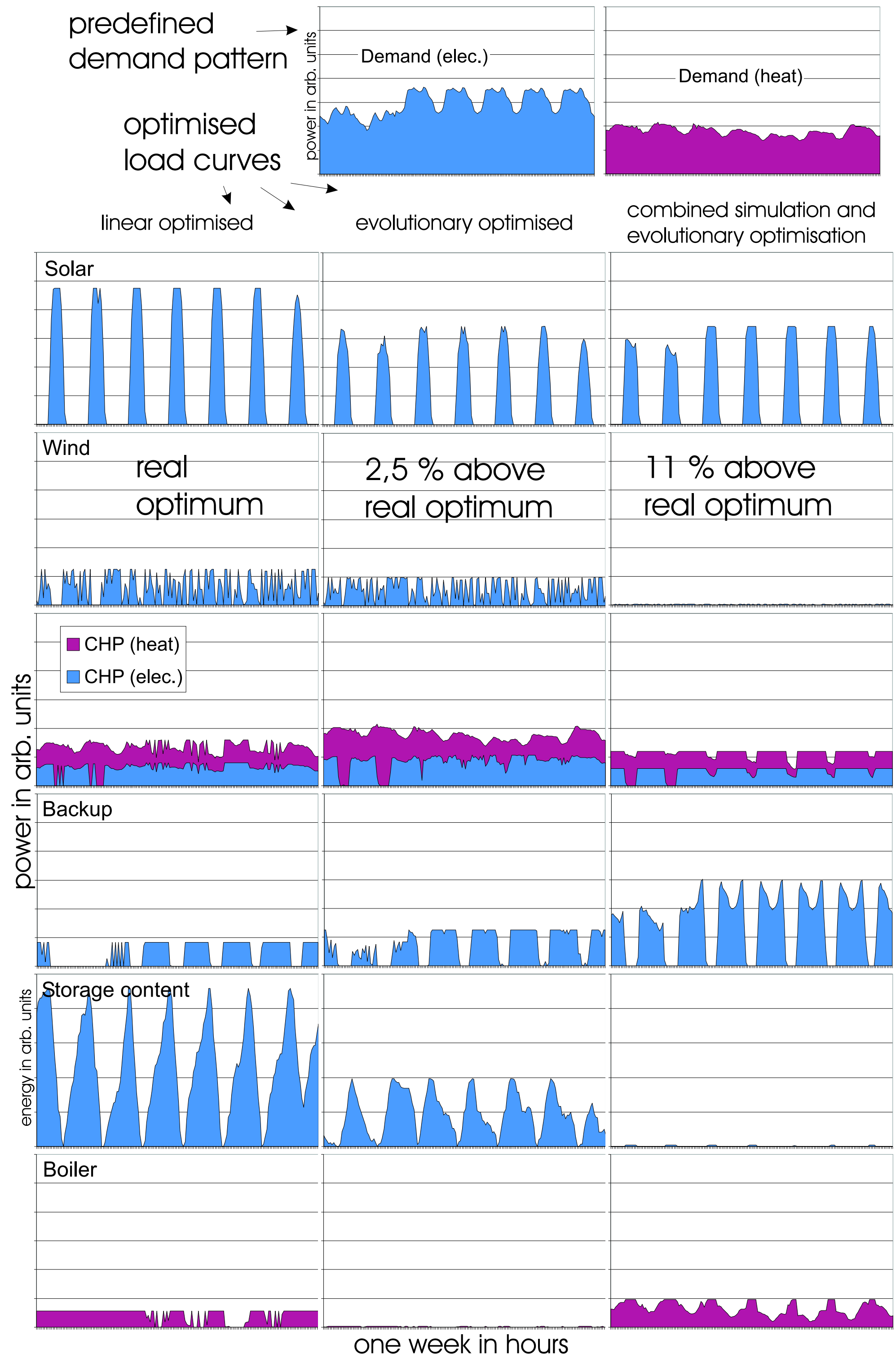


Figure 4.25: *Load patterns calculated using different optimisation methods. The linear optimisation method on the left side acts as benchmark solution because the scenario itself was fully linear. As a consequence, the other methods need to be compared with this benchmark.*

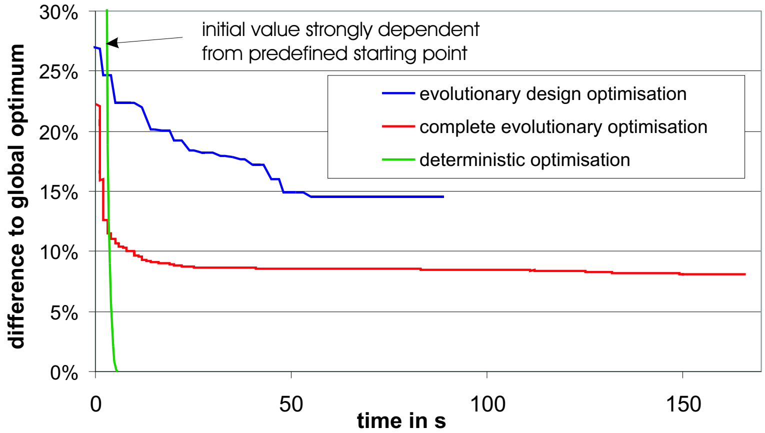


Figure 4.26: *Development of a solution over time in terms of the improvement of the objective function value.*

the outcome of the deterministic solution. In the case of the design optimisation solely, the model run in figure 4.25 is, in relation to the objective, about 11 % beyond the true optimum. However, the underlying simulation heuristic might not be yielding an operational optimisation in any case. In light of these and other likely modelling inaccuracies, it is concluded that the evolutionary optimisation method developed in this thesis is suitable for system modelling of this type.

The more interesting case is that of complete evolutionary optimisation, given in the middle of figure 4.25. Under complete optimisation, the resultant load curves indicate a solution that is about 3 % from the true optimum. This can be accepted as a manifestation of both: problem complexity and the nature of nondetermistic algorithms. In any case, the agreement is very encouraging and suggests that the method was aiming at the true optimum. This can be tested by looking at the solution state information as it developed. Figure 4.26 shows how rapidly the solutions converged, as indicated by the development of the objective function value.

Figure 4.26 shows for the complete evolutionary based approach arrives rapidly at a suboptimal system solution and then progress slows considerably. One might expect that this method would converge to the true optimum, but not without a considerable wait.

Nonetheless, these types of investigations represent an excellent starting point for future work on algorithm development and, in particular, the mutation and selection procedures.

The *design only* optimisation method suggests that, even as a basic implementation, it might prove very useful. It would appear that further work on the mutation procedure could well improve performance markedly. And, as a method, it is more likely to be of direct use in modelling projects not oriented to obtain a global optimum.

And, finally, evolutionary optimisation is particularly suited to those problems that remain out of bounds for deterministic methods. And even though evolutionary optimisation is not intended to compete with fast acting linear solvers, it is not significantly slower.

Chapter 5

Definition of end-point modelling in VLEEM

Under the back-casting approach employed in VLEEM, the end-point is understood to be a final boundary condition, selected in relation to the purpose of the associated model. This end-point can, to some extent, be regarded as a future equilibrium state related to global development that can, will, or should be reached. In the context of this thesis, the focus is on the energy sector and, more particularly, on sustainability. In this latter case, this equilibrium state also covers, as far as physics allows, climate stability and resource replenishment. Sustainability is a key concept in VLEEM. The selection of an end–point presents as a real challenge to modelling. The first step is to select the major determinants.

What must be included? What numbers are of interest?

The answers would normally cover all forms of energy and energy-services needs as well as all related resources. The relations between the major determinants are of chief interest.

5.1 Geography as major determinant

The word *geography* stems from the Greek "geo" (earth) and "graphein" (to write). Hence, geography is defined as follows:

The scientific study of the Earth's surface. Geography describes and analyses the spatial variations in physical, biological, and human phenomena that occur on the surface of the globe and treats their interrelationships and their significant regional patterns. [Encyclopædia Britannica, 2004]

Geography is concerned with a series of key issues which are of major importance for the energy system: climate, topography, population density, resources, etc.
It is important to understand the relationships between geography and the energy system, not only for actual systems but also for future systems. One illustrative example is the relationship between topography and population densities (see figure 5.1).

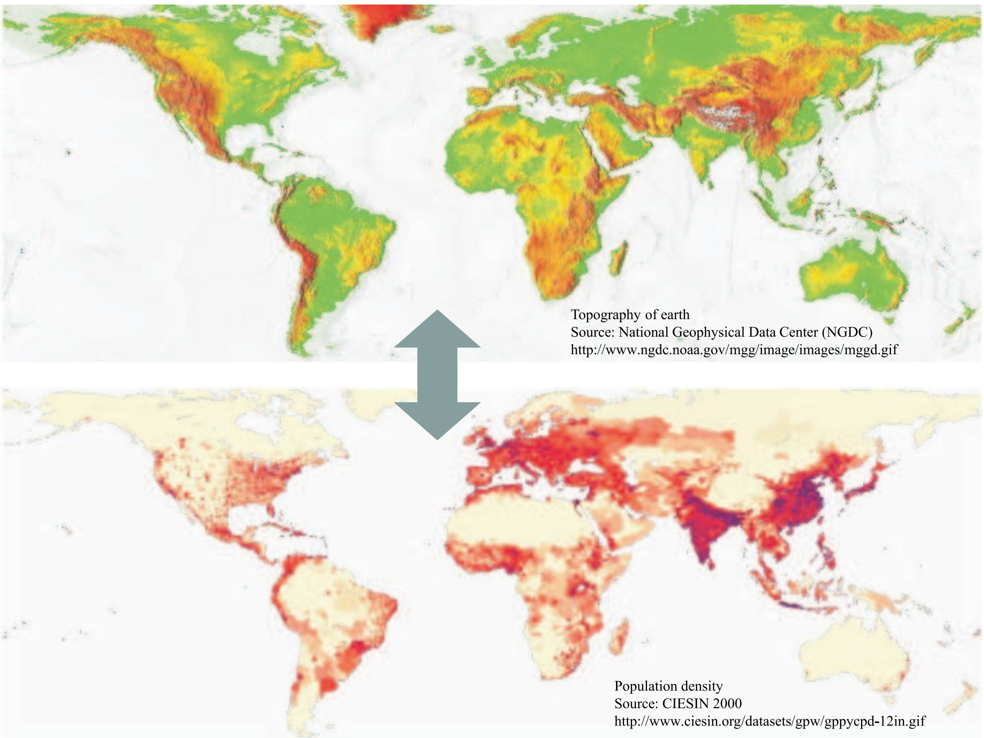


Figure 5.1: *Population density versus topography of the Earth. It is clear, more or less, that altitude and population density are inversely related.*

The diagram shows the topographical relief of the Earth in comparison to spatial population density. The following statement can be made by inspection (and some knowledge of technological capacity): *Settlement behaviour is strongly driven by topographical patterns.* With the relationship being approximately inverse.
Topographic change over the time scales relevant for energy system modelling are of second order, but topographical context has a strong influence on spatial population change.
Topography is only one of many potential influences on present and future energy systems. Further causal relationships include:

- soil, climate, topography ⇒ biomass potential

- fossil resources, climate impacts ⇒ restrictions on fossil fuel usage
- lifestyle, demographics , spatial population density, cultural aspects ⇒ end-use energy consumption
- etc. ...

All these aspects show, particularly on a global scale, strong spatial dependencies. To depict (or represent) an energy system, all of these influences should be identified and included where possible.

Due to the long term and global scope of VLEEM, such correlations are of major interest, especially in the context of ongoing globalisation process. An appropriate model, albeit in a simplified manner, needs to match all major energy consumption patterns to the available and/or potential supply patterns. Very often the optimal supply locations – like oil today – are far away from the major demand locations. An initial consideration of these issues is outlined in figure 5.2.

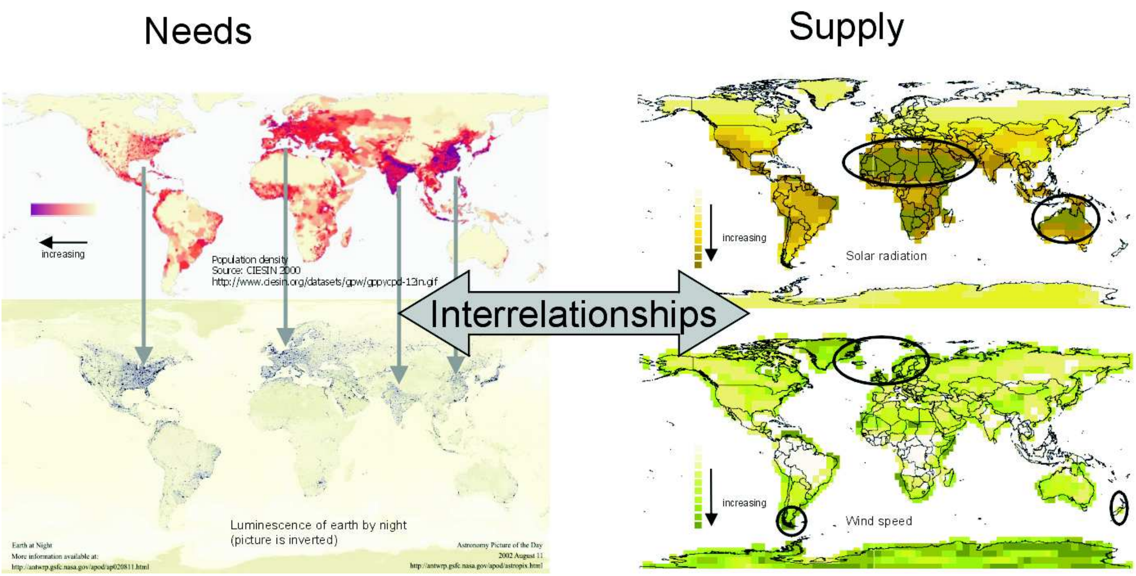


Figure 5.2: *An initial consideration of the global distribution of energy needs and supplies. The geographical interrelationships between demand obligations and supply potentials are a major consideration in end-point definitions.*

Spatial population density can be identified as a major driver for energy demand. This determinant, combined with others like living standards, social behaviour, culture, and so forth can be used to generate an estimate of future energy needs.
On the other hand, the supply side shows a different spatial distribution of energy related endowments (in figure 5.2, just wind and solar are considered). Moreover,

transporting energy over long distances, be it by wire, pipe, vehicle, or ship, is normally expensive in financial, energetic, and environmental terms.
The key message is therefore that both demand and supply have a strong dependency on geography. Moreover spatial disaggregation is required to capture these issues adequately in models. And that includes both demand and supply.

The end-point design should probe the feasibility of a specific technological solution, in any case it depends on on the geography.
TASES applies a least cost approach to determine the capacities and the scheduling of the components – like power plant – of the energy system. This approach offers the chance to describe simple economic relations, especially as economic weighting between investment and fuel cost and the various competing components.

One challenge of the end-point design relates to the required database. And relevant questions include: *What variables and parameters will have an impact? What level of disaggregation is required? What are the underlying relationships?*
If one aspect of the supply side (for instance, solar PV) needs highly disaggregated information, related parts of the system - including demands as well as sources – may need to be examined at the same level of dissaggregation. Therefore it is necessary to develop an idea of how best to process and combine the available information to reach a common level in the database.
To this end, a very extensive database with a high geographical resolution has to be prepared in order to enable the modelling of various end–point scenarios.

An illustration of location-dependent counteraction is given next, in order to demonstrate why a high level of modelling detail is necessary.

5.1.1 Illustration of geographical dependencies

One topical question is the future role of solar photovoltaics (PV). When will this technology move from niche markets to mass markets? And how will this happen? It is self-evident that the actual cost band for PV energy is far from competitive with conventional generation, in most applications. Nevertheless one argument applied to the prospects for PV concerns cost reduction by mass production. This can be formalised using learning curves, which describe the cost reduction in dependence of the cumulative production:

$$Cost(2 \cdot \mathbf{CUM}) = PR \cdot Cost(\mathbf{CUM}) \tag{5.1}$$

with

CUM	=	cumulative unit production over time
PR	=	progress ratio
$Cost(\mathbf{CUM})$	=	unit cost as a function of output

Doubling the cumulative production will reduce the specific unit price by PR:

$$Cost(\mathbf{x}) = PR^{\log_2(\frac{\mathbf{x}}{x_0})} Cost(x_0) \tag{5.2}$$

where

x_0	=	installed PV capacity at initial time step
$\mathbf{x}$	=	cumulative PV capacity until time step t

while the integral, and therefore the cumulative financial effort in a time range from t_1 to t_2, is given by:

$$\int_{t_1}^{t_2} Cost(\mathbf{x})dx = \frac{PR^{\log_2(\frac{\mathbf{x}}{x_0})}\mathbf{x}\ln(2)}{\ln(2) + \ln(PR)} Cost(x_0) \tag{5.3}$$

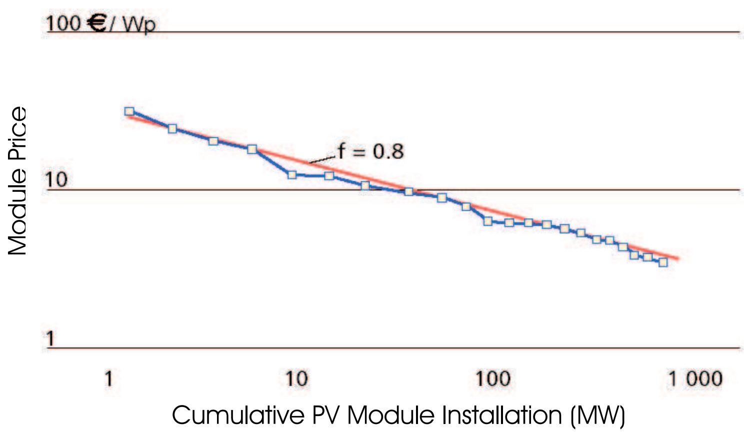


Figure 5.3: *Experience curve for PV modules* [ISE, 2001].

The development of PV module in the past are available (figure 5.3), which then prompts the question: When will it be competitive to install PV? Under which circumstances and conditions? What subvention effort is required to reach that point?
One plausible scenario is that PV will become competitive as peak load plant. The regional *and* temporal context of solar radiation must be considered.

The high time resolution provided by the TASES approach enables intermittent technologies, including PV, to be adequately captured. Intermittency is characteristic of most renewable technologies. A scenario involving geographic and temporal dependencies is presented next, to demonstrate the capabilities of TASES in this regard, with linear, rather than evolutionary, optimisation being used.

In this simplified model the supply system is described by a connection to a high voltage grid supplying arbitrary amounts of electricity at constant prices, a gas turbine and PV modules. The demand pattern is extracted from real world demand values measured in a middle sized south German city. The values are given in an hourly resolution. The situation is run twice, first in southern Germany and again in southern Spain. For the purpose of illustration, only the solar insolation data is altered (as per [S@tel–Light, 2002] as explained in section 5.3.1). The insolation data relates to 1997, as does the demand data. Other assumed values are given in table 5.1.

Scenario assumptions			
Process	**Installation Cost**	**Activity Cost**	**Efficiency**
Base load	-	EUR 2.0e–2 /kWh	1 (cost related to output)
Gas turbine	EUR 400.00 /kW →EUR 3.0e–3 /kW /h	EUR 3.2e–2 /kWh (restriction by CO_2-tax) EUR 1.6e–2 /kWh (business as usual)	1 (cost related to output)
PV	matter of investigation (cost / collector surface in m²)	-	0.25

Table 5.1: *Assumed parameter values for the scenario. Facilities are assumed to have an economic life of 30 years and face a discount rate of 5 %. The scenario constraints are intentionally chosen so that the PV installation can compete against the other supply options.*

The scenario parameter values are selected from the perspective of a local decision-maker. And the specified demand has to be covered by the available supply options. Therefore the grid import option is provided with an assumed high specific cost, the gas turbine has a low capital up-front investment and a high operational costs. The PV panels have a conversion efficiency of 25 % and can also be built up to cover day-time demand and compete with the other techniques. The resulting interactions are considered for different PV investment costs, as given in figure 5.4.
Figure 5.4 shows each of the three supply options in relation to their relative shares, while the installed cost of PV varies by a factor of 10. It is self-evident that market entrance for PV is strongly dependent on the geographical location as well as on the cost and operational attributes the other plant in competition. The uptake rate

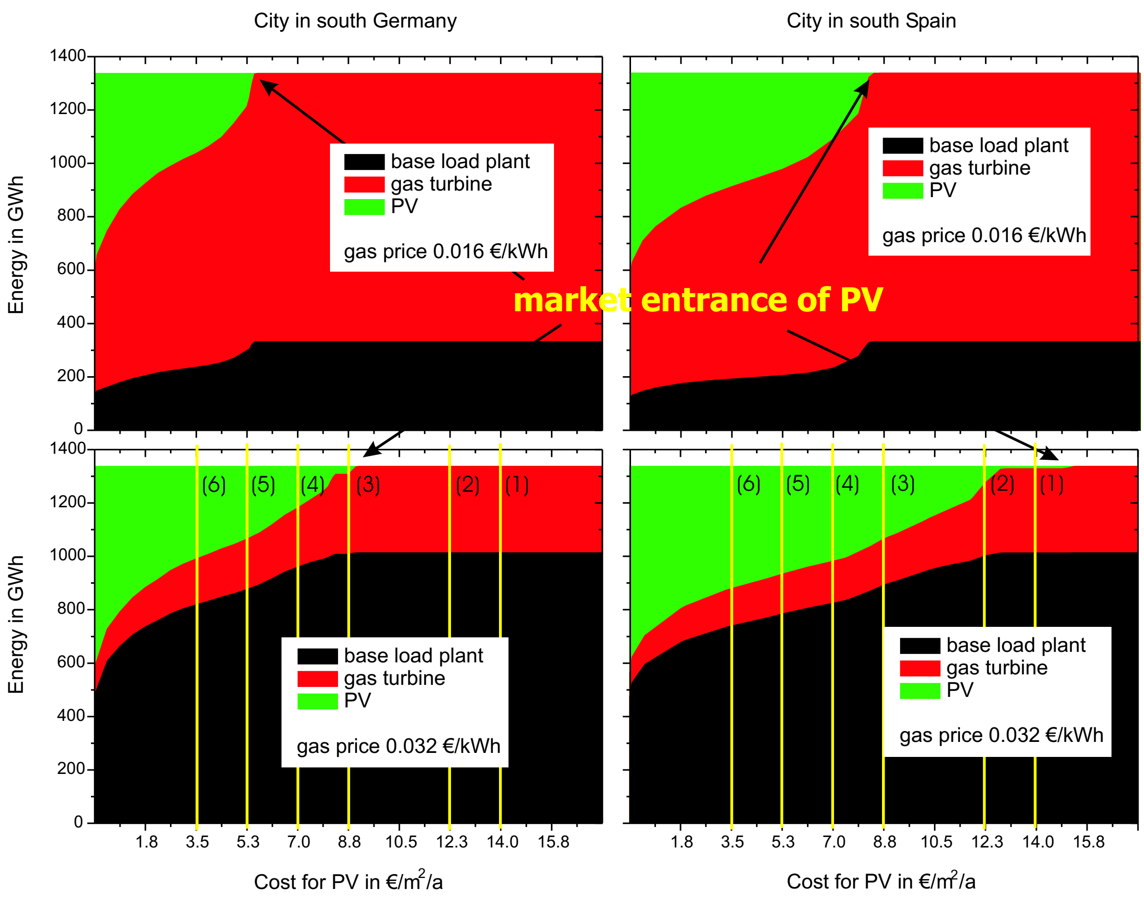


Figure 5.4: *Relative shares of PV in relation to changes in PV installation costs, gas price, and solar resource. Load curve snapshots for the PV cost assumptions marked (1) through (6) are shown in figure 5.6.*

is also of interest. One way of gaining information insight into uptake rate is to investigate the duty behaviour of the other participating supply technologies.

Figures 5.5 and 5.6 show a load curve section (snapshot) for a winter and a summer week under different cost assumptions. One outcome is that PV enters the market by addressing system peaks. That is due to the fact that peak load demand coincides with peak insolation. In terms of the two locations, PV cost reductions (beginning with cost structure (3)) which support limited peak load contributions in southern Germany have enabled installed capacities in southern Spain that meet the entire base load at times. The absence of electricity storage means that PV can only contribute to day-time demand and hence other supply technologies need to be present.

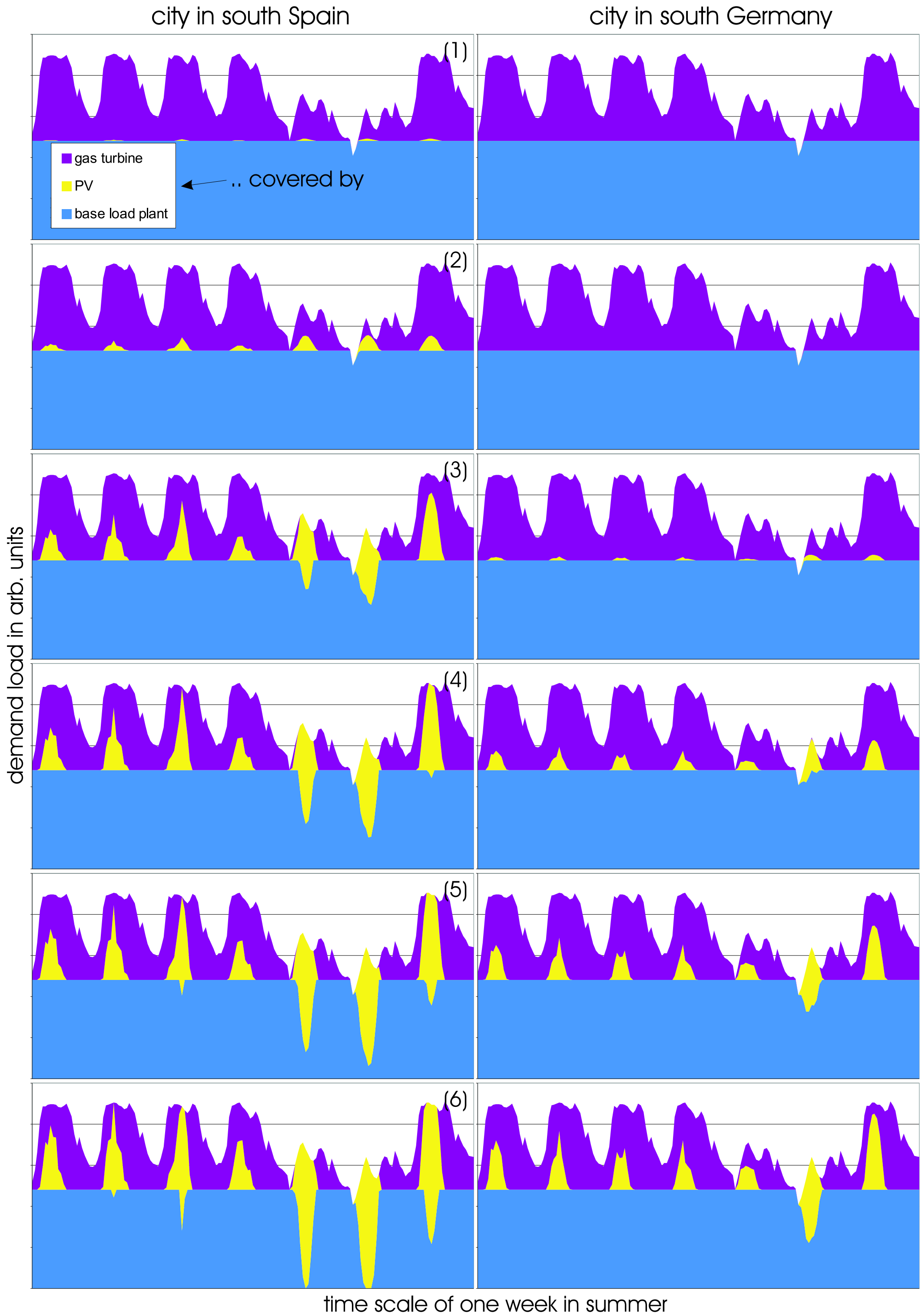


Figure 5.5: *Load curves for a winter week showing the relative shares of participating technologies under different PV cost assumptions (1) through (6). The gas price was held at Euro 0.32/kWh.*

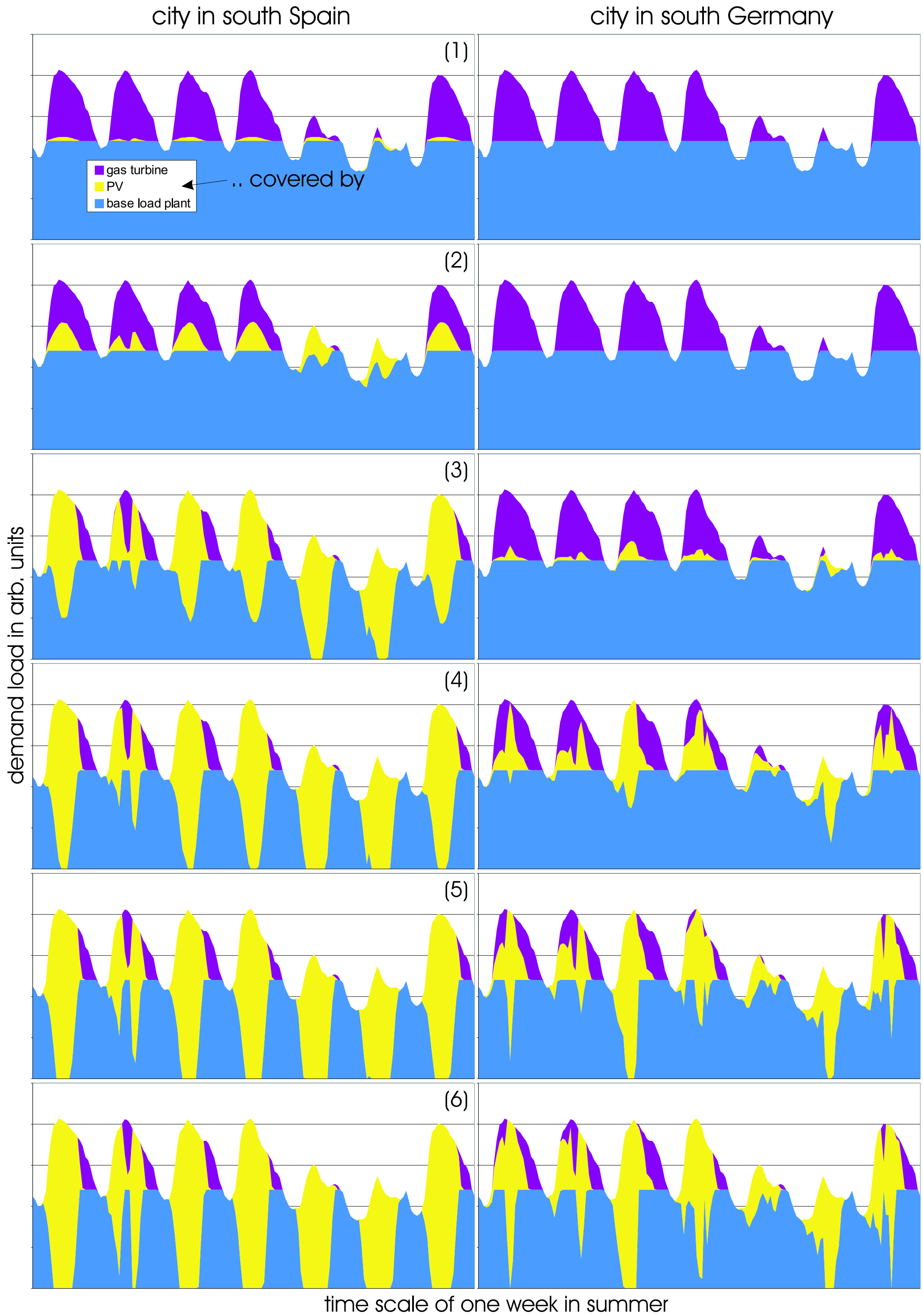


Figure 5.6: *Load curves for a summer week showing the relative shares of participating technologies under different PV cost assumptions (1) through (6). The gas price was held at Euro 0.32/kWh.*

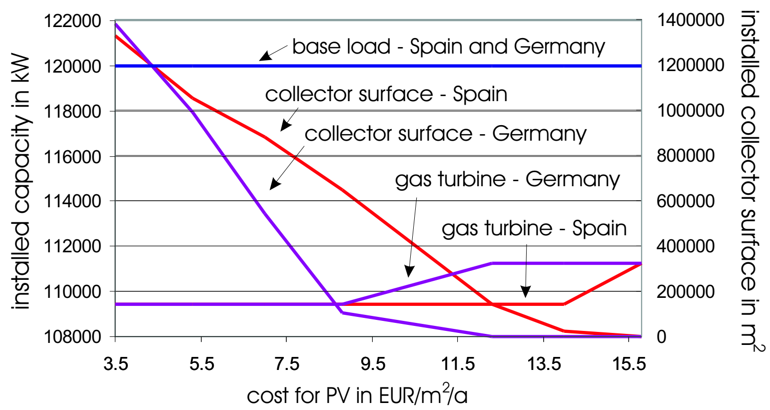


Figure 5.7: *Necessary installation capacities, depending on assumed PV costs to make the scenarios feasible, considered for the "high gas price" case.*

A further outcome of this fact is shown in figure 5.7. PV replaces certainly a lot of the energy production, but it is unable to reduce the capacity of backup technologies. First PV replaces a small fraction of the peak load demand with decreasing costs also part of the base load is supplied by PV.

This modelling assumption is only one of several possibilities. Another, possibly more realistic one, is the assumption that base load is not purchased in a capped capacity and actually consumed amount but by a forecast of the constant base load segment with a per kWh cost that is independent of utilisation.

With regard to the earlier question of which interventions might be necessary, an answer can be gleaned from the results.
With respect to PV, per m^2 costs are converted to the more usual per kW-peak (kWp) cost using an insolation value of 800 W/m^2. This latter parameter allows the point at which PV becomes marginally competitive to be calculated, known as the *break-even* point. This information can then be incorporated into the prevailing learning curves.
One obvious result from this figure is that, especially in the case of a high gas price, the competitive PV cost in south Spain is nearly twice as high as for a location in south Germany. The location of these values in the aforementioned learning curve (figure 5.9) provides a statement regarding the gap between actual installations (and related prices) and predicted installations based on the learning curve to reach this competitive PV cost assumptions.
The triangle defined by the learning curve and the point of intersection between actual installations and competitive cost assumptions belongs to certain subvention

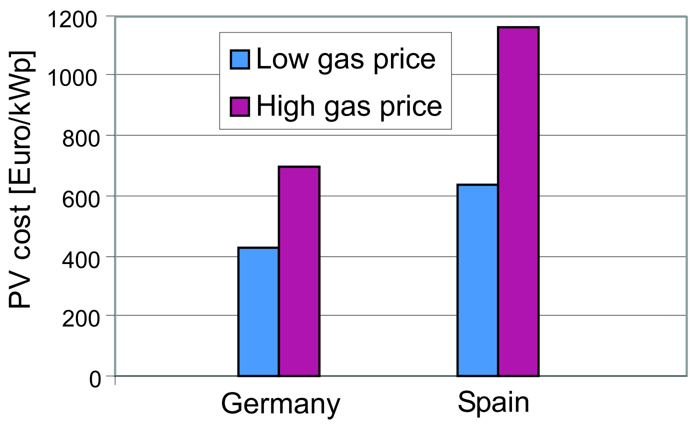


Figure 5.8: *Break-even costs for PV for the scenario locations in Germany and Spain. The estimate is made for two different gas prices.*

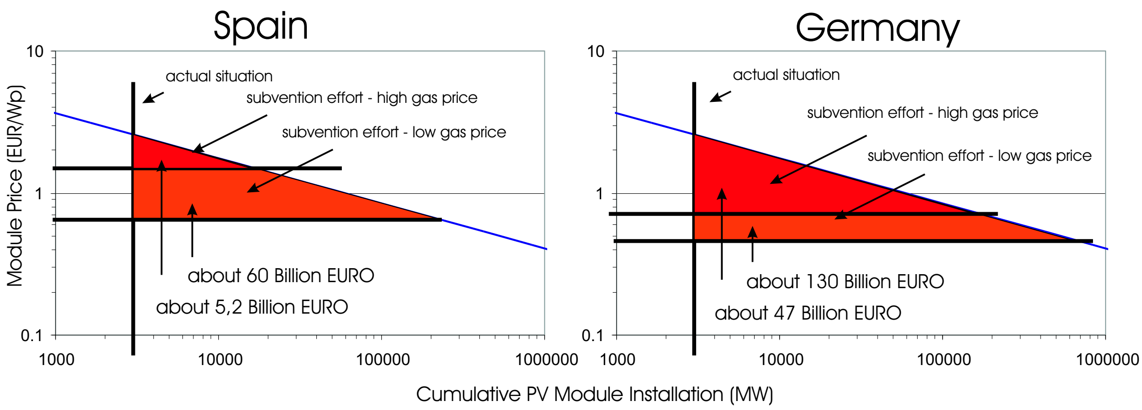


Figure 5.9: *Graphical explanation of the integrated subvention cost for PV under outlined conditions.*

efforts, necessary to reach the point of competitive PV costs.
The desired aim is certainly to keep the area enclosed by this triangle as small as possible. This can be influenced by several conditions. One is, without question, the geographical dependency. It is obvious that subvention efforts for the case in hand are less in southern Spain than in southern Germany. But alongside this, the external circumstances can also play a major role. As outlined in the scenario, a strong dependence from prevailing gas prices is evident. The integration of these various influences displays the aggregated subvention value in Euro. This figure varies, depending on the scenario assumption, from 5 billion Euro to 130 billion Euro.

The purpose of providing the above scenario is not only to motivate the need for geographically disaggregated data acquisition but also to demonstrate the need to use a high temporal resolution when comparing and selecting various technologies. Of course this is done in a very technical manner but this simplification is the reason why an examination on such issues is at all practicable.

5.2 GIS support for end–point design

Because high geographical resolution is required for the end-point modelling, the question then arises as to how best to manage this effort. Especially due to the geographic aspect, a geographic information system (GIS) might provide a sensible approach.
GIS can be defined as a system of hardware and software used for the storage, retrieval, mapping and analysis of geographical data. GIS differs from computer aided design (CAD) and other graphical computer applications in that all spatial data is geographically referenced to a map projection in an Earth coordinate system. The range of applications for GIS is wide. In general, any issue based on geographically referenced data-sets can be treated with such a system. The case in hand involving modelling energy systems on a geographically disaggregated scale contains various tasks influenced by geographical considerations:

- determination of spatially-based consumption patterns,
- selection of suitable locations for plant and storage facilities,
- inclusion of distance and connectivity information in relation to geographical energy flows.

All these challenges can benefit through use of GIS tools. The normal approach is layer based, as shown in figure 5.10.

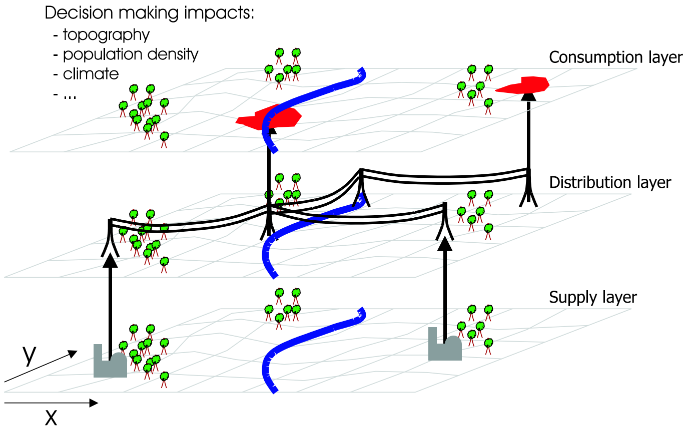


Figure 5.10: *Example of an energy system treated with a GIS tool. Different tasks are managed in different layers which are connected via a spatial reference system.*

Hence different issues related to different items are administrated in dedicated layers which share a common interface of geo-referenced addressing.

One popular common GIS tool is ARCView. ARCView combines all mentioned issues on a very plausible level and therefore it is chosen as interface for the necessary data management accompanying the modelling tasks.

5.3 Early end-point modelling attempts

With the notion of GIS in mind first visionary ideas find entrance in end–point modelling attempts. But first a suitable data acquisition process must be developed to capture consumption behaviour and resource potentials in relation to geographical distribution.

5.3.1 Data acquisition and preparation

In a first step, various datasets are prepared in a geographically referenced fashion. These datasets will be required later to define and setup the detailed specification of an end–point. For the time being, only data covering wind, solar insolation, and energy demand will be supported. Later on, this information system will be extended and used to describe and model demographic development, various items of importance for the energy demand, the energy transport infrastructure, and other energy resources of relevance.

Since the overall aim of modelling potential scenarios is to give a statement of pos-

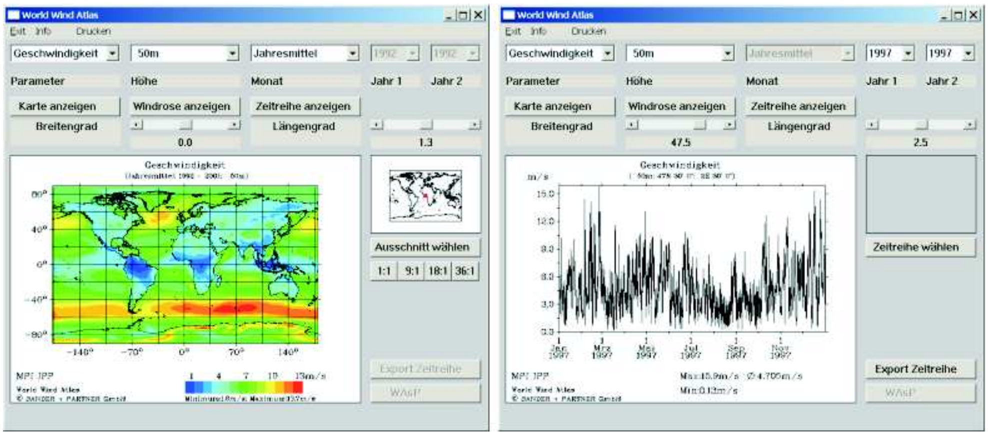


Figure 5.11: *Software interface of the World Wind Atlas* [WWA, 2002].

sible future energy systems, a special effort has first to be applied on the demand side.
One dataset that is utilised for modelling purposes is the UCTE (Union for the Co-ordination of Transmission of Electricity) statistical yearbook for 2000 [UCTE, 2001]. With respect to energy consumption, the UCTE dataset provides hourly load values for every third Wednesday and every third weekend for each month for every member nation. To obtain an hourly resolution for the complete year, these slices out of the statistical yearbook are "spread out" to form a complete data series with 8760 values (24 hours × 365 days) by linear interpolation. This procedure provides an hourly electricity demand load curve for the complete year 2000 for every member nation in the UCTE grid. Although this procedure cannot replicate the real load patterns, it provides a good first estimate.

It is necessary to model at the same level of disaggregation on the supply side. Indeed, the characteristics of highly intermittent renewable technologies (e.g. PV, solar thermal, wind generation) typically require an hourly resolution or even below.

A global dataset of wind velocities is provided by the *World Wind Atlas* [WWA, 2002]. Based on measured values, these datasets offer modelled wind speeds for landmass sites with a grid distance of 2.5° in longitude and latitude. Alternatively, national wind inventories can be used, which have higher time and space resolutions.
The base data present six hour wind speed values for the time horizon from 1992 to 2001 at 50m above ground. To enable suitable estimates of wind power potential, some method of calculating hourly (or other) deviations from these average values is required.

One approach is statistical and uses the Weibull distribution [GASCH, 1996].

$$f_w(\mathbf{u}) = \frac{k}{A} \cdot \left(\frac{\mathbf{u}}{A}\right)^{k-1} \cdot exp\left(-\left(\frac{\mathbf{u}}{A}\right)^k\right) \tag{5.4}$$

with

$f_w(\mathbf{u})$	=	function value of Weibull distribution
$\mathbf{u}$	=	wind speed in m/s
k	=	shape parameter ($k = 2 \rightarrow$ Rayleigh distribution)
$A = \frac{\bar{\mathbf{u}}}{\exp(\ln(\Gamma(1+\frac{1}{k}))}$	=	scaling parameter in m/s where Γ is the gamma function

The shape parameter k is an inverse gauge of wind speed standard deviation relative to the average wind speed. This value varies, as its name implies, depending on landform, time of day, and other influences, around the number 2. Some possible distributions are shown in figure 5.12.

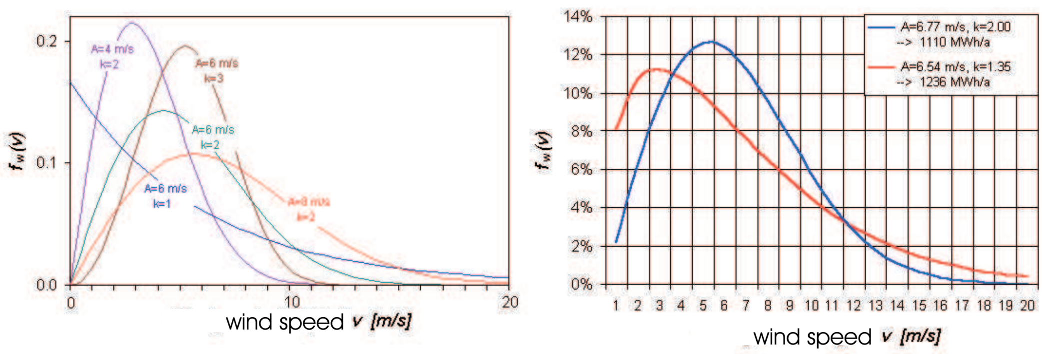


Figure 5.12: *Wind speed distribution for different shape and scaling parameters (left hand side) and their impact on energy harvest per year (right hand side) for a typical 600 kW wind turbine* [ALLNOCH, 1996].

It is obvious that the energy harvest per year is dependent on the assumptions made regarding the shape and scaling parameter (see figure 5.12 – right side) but, nevertheless, for the purpose of modelling within this thesis, the shape factor can be fixed to 2. This assumption forces the wind speed variations to adopt a Rayleigh distribution.
To establish an impression of a typical hourly wind speed time series, the scaling parameter A is set using the linear interpolated average wind speed. This means that an individual Weibull distribution is required for each time step. A synthetic

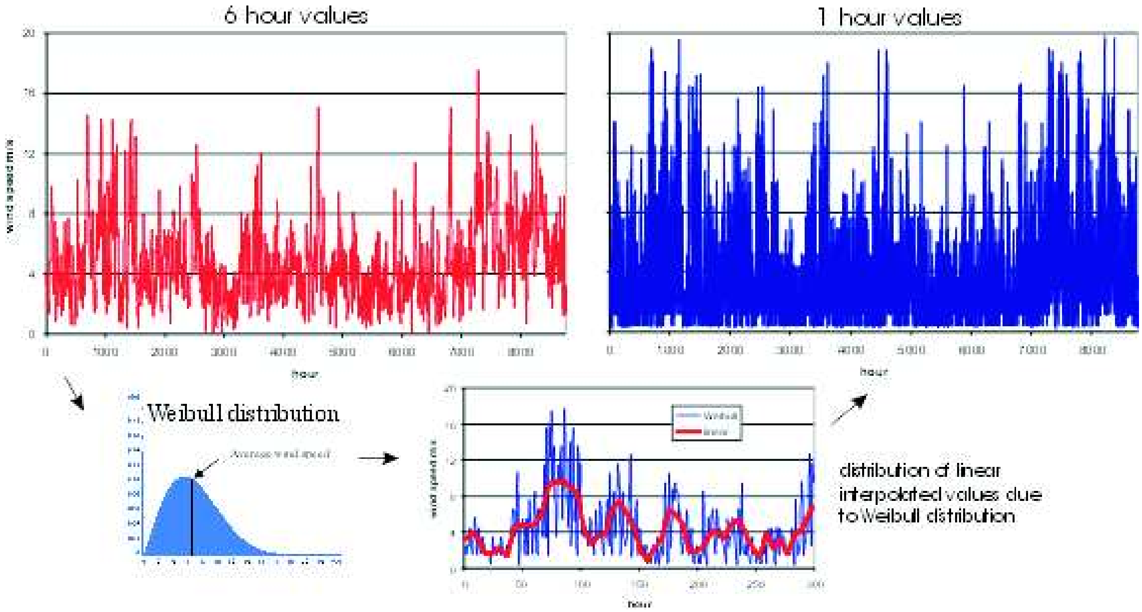


Figure 5.13: *Statistical interpolation of the empirical World Wind Atlas six hour wind data time series to an hourly distributed time series. The linear interpolation is dispersed by the probabilities given by a Weibull distribution.*

hourly wind speed is then generated by sampling this particular Weibull distribution at random.

The procedure outlined in figure 5.13 is suitable for extending the available six hour average values to one hour average values while still retaining the variable characteristic of real wind speeds.

The wind speed values are converted to electrical output using the characteristics of a representative 1.25 MW (rated power) wind turbine [WINDPOWER.ORG, 2004]. This electrical output is then provided as an input data series for the model.

A second global data set employed for modelling purposes concerns solar insolation. The NASA web site [NASA, 2002] provides suitable information (figure 5.14).
The NASA data is derived primarily from satellite measurements. The total (integrated) daily insolation on a horizontal surface at each degree of longitude and latitude is available for the decade June 1983 to July 1993.

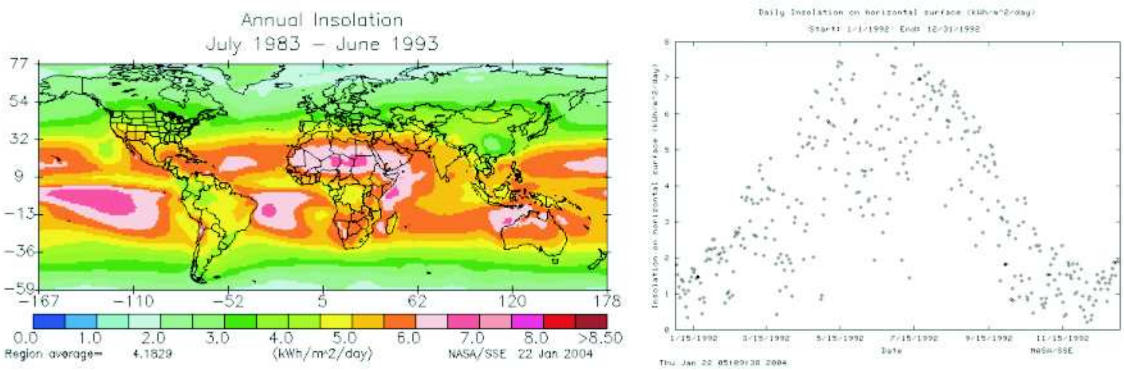


Figure 5.14: *Global solar radiation values from the NASA web site* [NASA, 2002]. *For each location, the total (integrated) daily insolation on a horizontal surface is given.*

This daily information can then be used to generate daily load curves by considering the location specific course of the sun, as shown in figure 5.15.
The following derivation shows how the geographical dependencies enter. The solar insolation on a horizontal surface can be found by calculating the normal component of the insolation vector related to this surface. This component is defined as follows:

$$\cos\Psi = \sin\beta\sin\delta + \cos\beta\cos t^* \tag{5.5}$$

where β defines the latitude and δ the declination of the sun relative to the Earth. The time dependency is included in the angle t^*. This angle is defined as:

$$t^* = \alpha + GMT\frac{15^\circ}{h} \tag{5.6}$$

t^* captures information about the latitude α and the time shift relative to GMT (Greenwich Mean Time).
Equations 5.5 and 5.6 allow the daily insolation values to be decomposed into hourly time series.

1992 was selected as the year on which to base estimates of wind and solar potential, due to the data availability. The temporally resolution chosen was hourly for one year - making 8760 values. And the geographic resolution chosen was every 5° in longitude and latitude, for landmasses only – making a total of 1200 intersections (see figure 5.16).
The correlation between year 2000 demand patterns and 1992 environmental data is clearly not absolute. But it is suitable for our purposes, particularly given that the focus of investigation is on future energy systems.

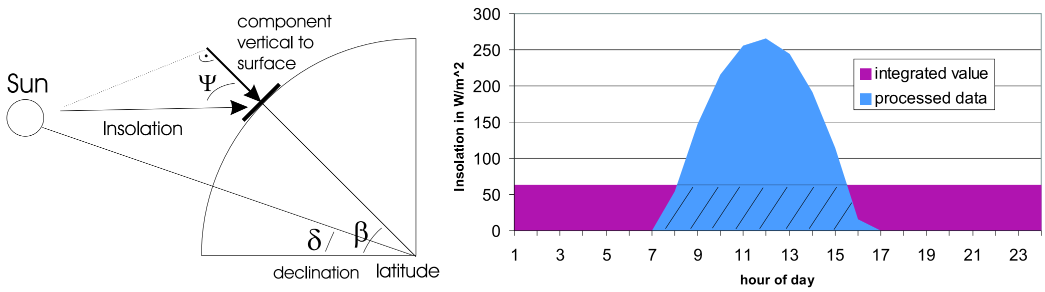


Figure 5.15: *Daily solar insolation information can be disaggregated using the following location-specific procedure. The left-hand side diagram shows the geometric dependencies at play and the right-hand diagram shows the result of applying these dependencies to a daily value. Secondary effects, such as cloudiness, are ignored for the purposes of this transformation.*

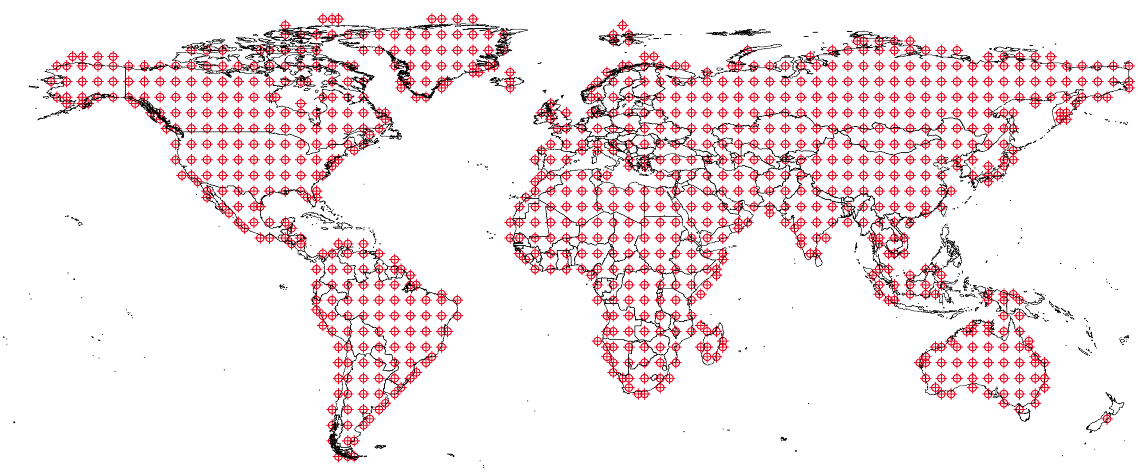


Figure 5.16: *Geographical meshing of wind and solar data for use in modelling. The arrangement covers each 5° increment in longitude and latitude for the landmasses only and contains an adjustment for coastal regions.*

In addition to the solar data from NASA, insolation data sets provided by the European *Database of Daylight and Solar Radiation* [S@TEL–LIGHT, 2002] are also utilised. This database allocates half hour solar radiation values for Europe from 1996 to 2000 and is available via the Internet. This data is also satellite-based and offers an additional distinction between entire radiation and direct radiation. The key advantage of this database is the fact that no additional preprocessing is required, but, on the other hand, geographical coverage is restricted to Europe.

5.3.2 Evaluation of a substantially renewable future for Europe

One innovative scenario for Europe is a future energy economy based only on renewable energy sources. Such an energy economy would look very different from the current non-sustainable system configuration. Any investigation into the feasibility of such an "energy future" should be able to present an order of magnitude assessment of issues involved.
Each member nation in the grid is represented in this scenario with one or two geographical points. These points are connected via amalgamated electricity transmission lines, as outlined in figure 5.17.

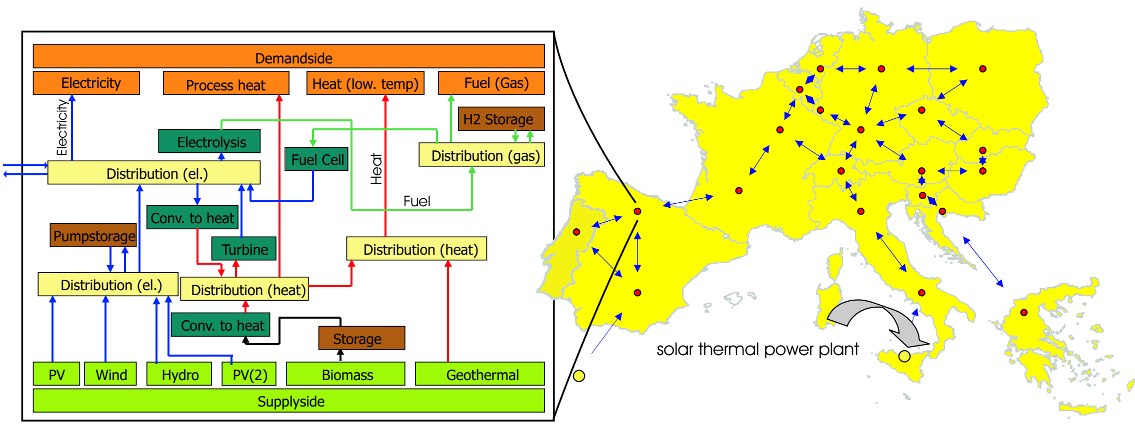


Figure 5.17: *High renewables scenario, adapted from the connectivity within the current UCTE grid. Each country is represented by one or two dots which are connected using electricity transmission lines. Each node represents the structure indicated in the zoom. This node pattern includes all supply, conversion, and demand facilities under consideration.*

Each of this nodes represents a complete supply and demand structure. The simulation is performed in hourly resolution and the assumptions made for the scenario are the followings:

- The complete energy demand is divided in four commodities – electricity, low temperature heat, high temperature heat, and fuel.
- Each node combines the outlined local conversion and storage structure (figure 5.17, left side) for four different commodities: electricity, low and high temperature heat and hydrogen.
- Each node is required to represent its own local consumption and supply potentials to other connected nodes. This means that energy supply and demand is able to be met non-locally as circumstances allow.
- Each node is, both on the demand-side and supply-side, forced to the country representing consumptions and potentials. The energy demand and the potentials for renewables are determined for each country individually.
- The only commodity that can be exchanged between single countries (nodes) is electricity.
- The capacities of the interconnections are, for practical purposes, unlimited.

Guided by the vision of a sustainable energy future, completely based on renewable energy sources, the purpose of the above assumptions are:

How can such a visionary scenario fit in the existing distribution system? And will it be compatible with sustainable development criteria?

TASES offers two ways to tackle this problem: *simulation* and *optimisation*. These two approaches differ first in the way the problem is articulated: in the case of simulation, the capacities of the system need to be identified in advance, while in case of optimisation the system capacities are determined using specified cost information for all technologies and commodities. Specific cost, in this context, is the relevant per unit cost expressed in terms of either capacity, activity, or commodity.
Depending on the modelling purpose, the complexity of a scenario can reach a level whereby optimisation attempts are limited (– due to either machine time restrictions or memory constraints, time and space complexity, respectively). Nevertheless, interesting conclusions about scenario behaviour can be also made by applying pure simulation. This approach provides, as output, all the load patterns in a given system. The difference in relation to optimisation is, in the latter case, plant capacities are a result of the optimisation. In contrast, plant capacities have to be specified in advance when using pure simulation.

The high complexity of many commonly encountered problems leaves simulation as the only practical approach, particularly if a year-long hourly resolution is used.

5.3.2.1 Dataset preparation

This section looks at dataset preparation issues associated with the scenario under development. This scenario is set in the year 2100. The projected energy demands are consistent with the assumptions made by [CHATEAU, 2002]. The

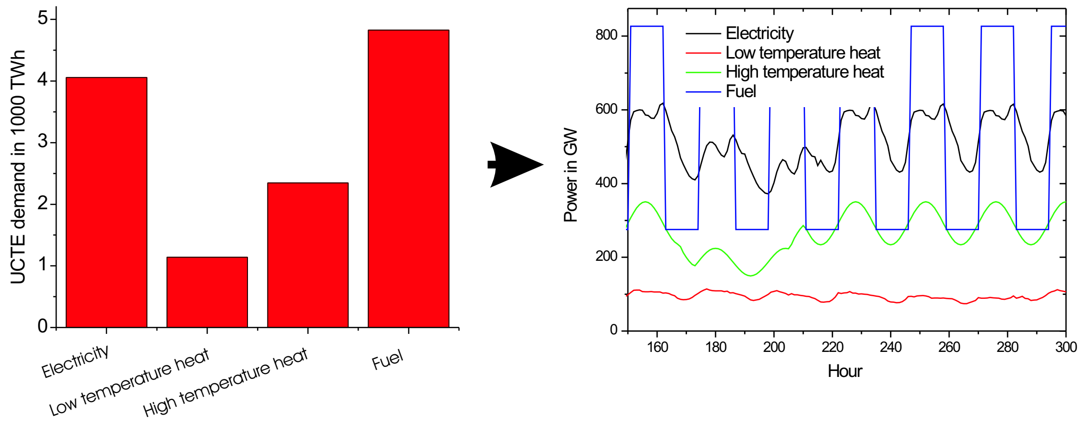


Figure 5.18: *Description of the energy requirements as evaluated in* [CHATEAU, 2002].

time-dependent electricity consumption patterns (load curves) were decomposed using the procedures given in figure 5.18 to produce hourly time series. A similar procedure is adopted for the remaining commodity types as follows (with electricity retained for completeness):

- *Electricity*
  The demand pattern is simply the load curve for the different countries, processed in the mentioned way for 2000 out of [UCTE, 2001].

- *Low-temperature heat*
  The demand pattern for low-temperature heat is extrapolated from the load curve of a district heat network in a representative south German city.

- *High-temperature heat*
  Process heat usage shows little or no seasonal dependence and only weak day/night correlation. A sine function is used to model this variation with an additional decline to account for weekends.

- *Fuel*
  Fuel demand is represented using a simple square wave function which allows a simple differentiation between day and night usage.

The above assumptions form part of the base constraints for the following scenarios.

5.3.2.2 Scenario assumptions and results

The opportunities for harvesting natural energy commodity flows (but not depletable stocks, for this scenario) depend strongly on the level of demand present and the range of conversion, storage, and transport technologies available.
The goal of the current scenario investigation is to place some of the published frequently encountered estimates of the technical potential for a sustainable energy future into perspective. This includes the required estimated energy demand and some feeling for the required transport and storage infrastructure. Emerging Technologies like wind and solar require new methods of analysis. Estimates of the potentials are, in the main, relatively coarse estimates relying on natural fluxes. This whole issue is rather preliminary. The intermittent nature of the energy flows is generally avoided.
A often quoted encountered statement is that only technologies using direct solar radiation will be able to meet most of the global energy demand on a renewable basis (this necessarily excludes biomass and wind) [Häfele, 1981], [WGBU, 2003]. Not surprisingly, this statement warrants further thought. But it is a reasonable place to start and the base case will be mainly designed around technologies using direct solar radiation. From which three further plausible cases where built. On this pattern three very fictive scenarios are applied: RENEWABLE, PV, and SOLAR THERMAL. The structure each node represents is outlined in figure 5.17.

	Scenario (RENEWABLE)		Scenario (PV)	Scenario (SOLAR THERMAL)
	Capacity	Potential [TWh]	Capacity	Capacity
PV (25% efficiency)	2035 km^2 (roof top surface) 30780 km^2 (150 m^2 / capita)		51300 km^2 (250 m^2 / capita)	
Solarthermal				37600 km^2 (110 m^2 / capita)
Geothermal (heat)		786 TWh		
Wind	315 GW			
Hydro		292 TWh		
Biomass		2030 TWh		

Table 5.2: *Supply capacities for three different scenarios based on the UCTE-based grid* [Lako, 1998], [European Commission, 1996].

The supply side is completely occupied by renewable energy sources, namely photovoltaics (PV), wind power, hydro power, biomass, and geothermal energy. These

UCTE countries					
Country	**PV** (km^2)	**PV(backup)** Ratio of total amount	**Wind** (GW)	**Hydro** (TWh)	**Biomass** (TWh)
Austria	48	2.34%	37.9	42.2	87.0
Belgium	46	4.10%	26.8	1.7	14.9
Croatia	30	0.68%	41.5	5.8	14.9
Czech	30	2.84%	19.8	2.3	14.9
France	360	21.01%	82.9	67.6	376.5
Germany	600	23.11%	53.6	23.6	238.0
Greece	54	2.19%	22.6	4.1	144.3
Hungary	42	1.87%	0.2	0.2	120.1
Italy	324	14.82%	45.2	50.3	240.3
Luxembourg	3	0.29%	12.6	0.9	2.0
Netherlands	72	3.61%	13.9	0.0	7.5
Poland	120	6.89%	0.0	4.0	87.0
Portugal	48	1.78%	0.0	11.6	76.8
Slovak	27	1.37%	0.0	5.0	14.9
Slovenia	30	0.54%	0.0	3.5	7.5
Spain	156	9.73%	75.7	31.4	575.9
Switzerland	45	2.83%	0.0	37.8	7.5

Table 5.3: *UCTE member countries with their individual contributions to the cumulative potential estimates given previously in table 5.2.*

sources can be converted and stored according to the indicated scheme. The difference in the three identified scenarios is only the assumed installed capacities on the supply side. The respective numbers are outlined in table 5.2.

The break down by UCTE member country is outlined in table 5.3. Wind [Lako, 1998] and solar [European Commission, 1996] numbers are based on capacity boundaries while hydro power and biomass are based on direct energy potential estimates. A smooth seasonal dependence in hydro power with a peak in summer is assumed while biomass shows a flat energy yield during the year. It is assumed that geothermal energy is only used to cover low temperature heat and therefore the demand of low temperature heat is reduced by the available potential of geothermal energy in order to remove this part from the numerical modelling process and thereby reduce computation time.

As the first example (scenario PV), PV is considered to be the primary energy source in 2100. The necessary energy storage would be accomplished via hydrogen. A total of 77e+09 m^2 (three percent of rooftops) would be covered by PV panels (the

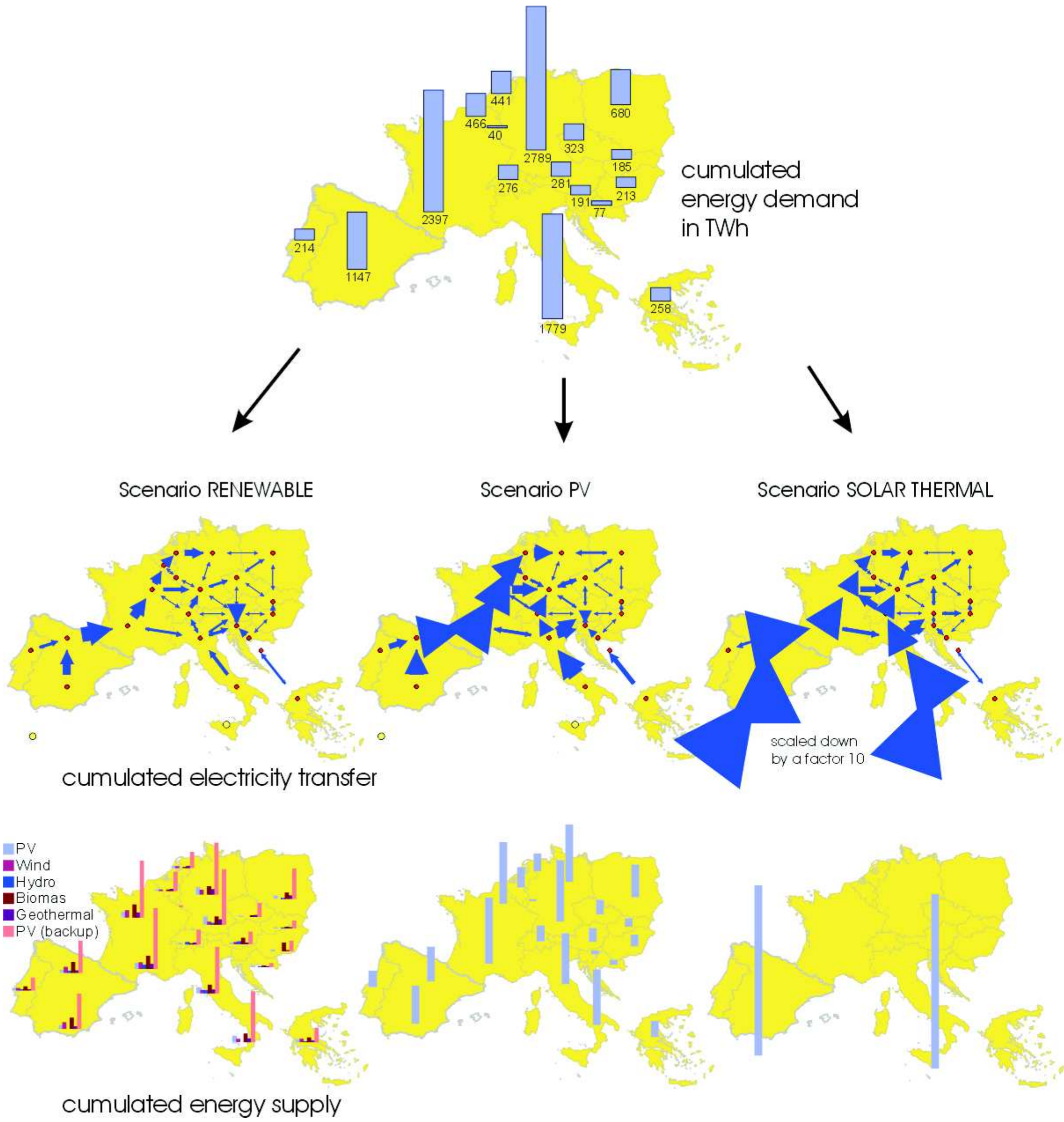


Figure 5.19: *UCTE scenarios with country-specific energy demand. The top diagram shows the assumed consumption. The middle and bottom diagrams show the scenario-specific energy flows as well as the total energy harvest (the bars). The thickness of the arrows marks the aggregated load for each transmission line over the modelled time horizon.*

active cells are assumed to cover 2/3 of the area). This is 206 m^2/capita. A storage capacity beyond 5000 TWh (see figure 5.20) would be necessary, which has to be seen in relation to the existing underground space for natural gas. In Germany, a volume of 19e+09 m^3 of storage volume is available. This corresponds to an energy content of 100 TWh (for hydrogen at a pressure of 20 MPa). The example is certainly extreme, but it offers the chance to debate some of the major issues. Would such a system violate present day sustainability criteria? Certainly, the energy conversion system would be a new vector in the context of cultural activities like urbanisation or the traffic system. The per capita land demand would be in the order of the current land demand for roads in OECD countries, which is roughly between 100–400 m^2, given a street width of 10 m [EST, 2000]. In which case, the existing roof space could only host a small fraction of the collectors required. Supplying the storage space seems even more demanding, but not totally infeasible.
The seasonal variation in PV makes it necessary to store large fractions of the energy for rather long time periods, so the conversion to hydrogen is unavoidable in this situation.

In a further scenario (RENEWABLE) the previous extreme case is now altered. Other renewable sources, like biomass, geothermal, hydro and wind can also contribute to the energy mix. These potentials are listed in table 5.2 and table 5.3. One of the central questions is, to what extent could the huge requirement for storage capacity be reduced?
So in this scenario, the estimated potentials for renewables are assumed to be utilised for energy purposes. Additionally, a back-stop assumption of solar collector surface per capita is added to satisfy all needs not met by the other potentials. The selected storage facilities, except for hydrogen, are intended to smooth daily fluctuations between supply and demand load and accounts for 1.4 TWh over Europe. Only the hydrogen storage facilities have no prior capacity restriction in order to guarantee the feasibility of the scenario.
Turning attention to the supply side, only one quarter of all energy needs can be covered by the non-PV potentials (see figure 5.20). The remainder is assigned to the PV back-stop facilities. But as a result of the more balanced primary energy mix, hydrogen storage is reduced to 2600 TWh from 5000 TWh. The use of biomass also partially counterbalances the uneven distribution of solar insolation over the year.

A further response (scenario SOLAR THERMAL) would be to install concentrating solar thermal power plant in northern Africa and send electricity to Europe. The seasonal insolation variation in northern Africa is less pronounced than in Europe. And the resource is also better too, primarily due to a higher direct radiation component. So the assumption in this scenario is that all needs are satisfied by solar thermal power plant.

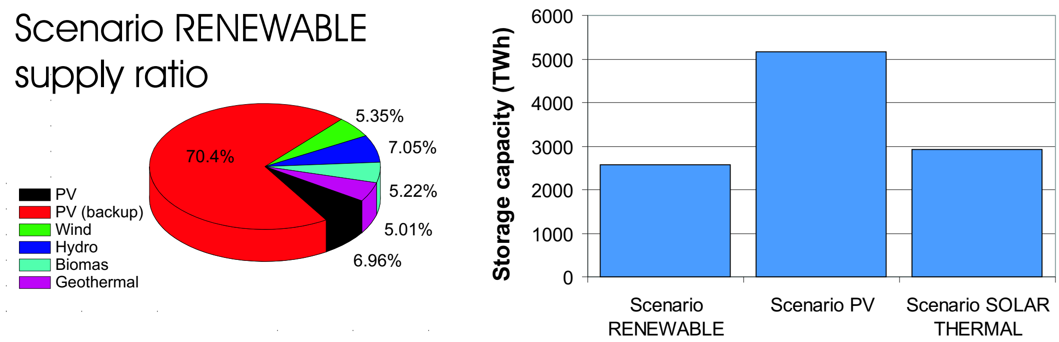


Figure 5.20: *Consolidated modelling results, showing outlined ratio of participating supplies in the renewable scenario (left side) and claimed aggregated storage capacities for all contemplated scenarios (right side).*

The location-dependent potentials for wind power are processed as outlined in section 5.3.1. All solar radiation data, including global radiation for PV as well as direct radiation for solar thermal plant are sourced from [S@tel–Light, 2002].

The simulation of these three scenarios provides an interesting picture of the future. The results be articulated in various ways. One straightforward approach is to visually depict the load carried by each individual transmission line. The spatial resolution of the model approach enables a complete disaggregation of energy flows, as shown in figure 5.19.
Each transmission line is assigned an arrow in which its size is related to the total load is carried over the model time horizon. Very obvious is the increasing utilisation of the grid with the limitation of the scenario to solar power facilities and mainly in the case of solar thermal plant restricted to locations in the south.
Out of these aggregated values, capacities are estimated, on the assumption that all transmission lines are working under full load for the complete year. This assumption is based on the fact that each individual node has sufficient storage capacity to smooth any fluctuations which arise.
The ratio of values from the three scenarios and the actual interconnection capacities in the UCTE grid are shown in figure 5.21. Each single transmission line is listed with its estimated capacities for the indicated scenarios relative to the actual capacities in the UCTE grid. With respect to the RENEWABLE scenario about 2/3 of all installed interconnections satisfy the sought requirements. In the pure solar scenarios PV and SOLAR THERMAL the situation is less favourable. The reason for this arises from the fact that the interconnections are not only used to compensate for supply and demand imbalances between neighbouring countries, but

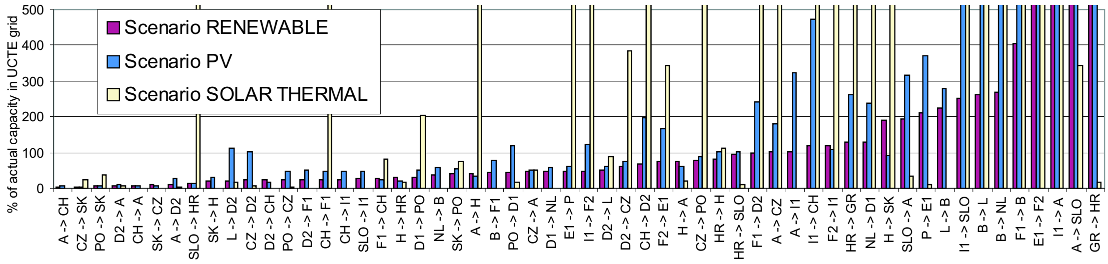


Figure 5.21: *Indicative ratio between the values arising out of the three modelled scenarios and current capacities of the UCTE grid.*

also to transport energy over several nodes. This is particularly so in the SOLAR THERMAL scenario where large amount of energy needs to be transported from south to north.
In general, all the scenarios considered focused on solar energy, which explains why the sought interconnections in the southern part of the UCTE grid exceed the actual capacities by factors beyond 5.

Also this numbers are very fictive ones the enable to get a feeling for feasibilities and infeasibilities on certain scenario patterns. Their understanding is fundamental for the end–point modelling issue.

5.3.3 The vision of Global–link as an option

The energy system is already today strongly linked in the two major commodities: oil and coal. Gas is transported over distances of more then several thousand kilometers. In future also a link of the electricity system and an emerging hydrogen system might evolve. The pioneer in thinking about a global energy grid was R. Buckminster Fuller. He developed a first sketch of a connected world via electricity transmission lines (figure 5.22).
For sure, 30 years ago such ideas were only visions dedicated to future decades. But the boundary conditions have changed enormous during the last years. While 30 years ago electricity could be transported efficiently only over about 500 km, new technologies enable economical transport distances beyond 6000 km [Klein, 1994]. On this basis, electricity transport might be competitive on scales far beyond local tasks. That means electricity exchange between the northern and southern hemispheres may become feasible on economic grounds.
In the context of a sustainable development, which is often associated with the uptake of renewable energy sources, the development of a global grid becomes a major

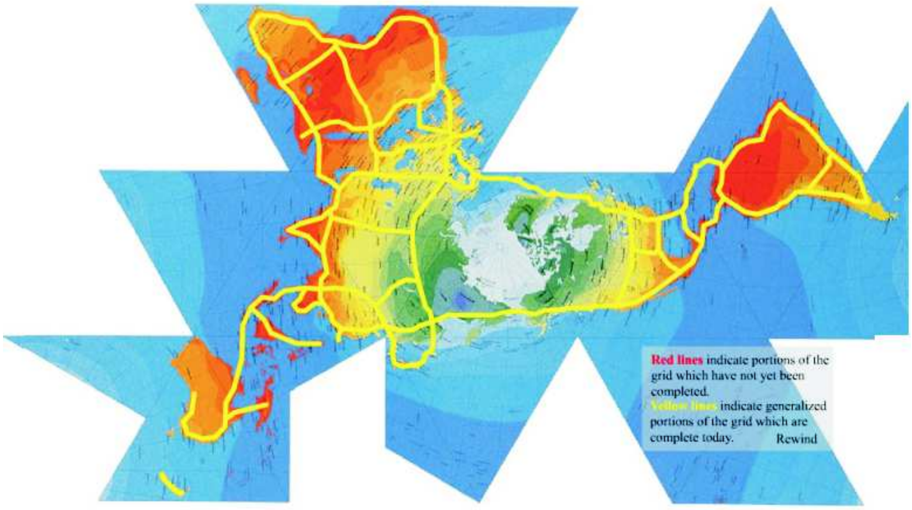


Figure 5.22: *Dymaxion projection of the world with the vision of a global electricity grid, as envisioned by Buckminster Fuller in 1970.*

attraction. The most compelling reason is the opportunity to harvest renewable energy at locations which are, in general, far away from consumption areas. Some examples might be:

- large untapped hydroelectric sites in Latin America, Canada, Alaska, Siberia, Southeast Asia and Africa,
- tidal sites in Argentina, Canada, Siberia, China, Australia and India,
- solar potential circles the earth in Mexico, USA, Africa, the Middle East, Russia, India, China and Australia,
- geothermal potential around the Pacific Ocean "Ring of Fire", in the Rift Valley of Africa, and Iceland.

Due to the fact that electrical energy has an exergy/energy ratio of unity, it is reasonable to transport it also in this form. Therefore a global linked electricity grid might be useful.
Another advantage of an electrical connected world is the potential ability to smooth local fluctuations in energy supply sources and in demand usage. One example is the outcome of global distributed wind turbines, which show one of the highest levels of natural variability (figure 5.23).
When connected to a global grid, such fluctuations will tend to be smoothed to an average which shows a much smaller deviation in regard to consumption load

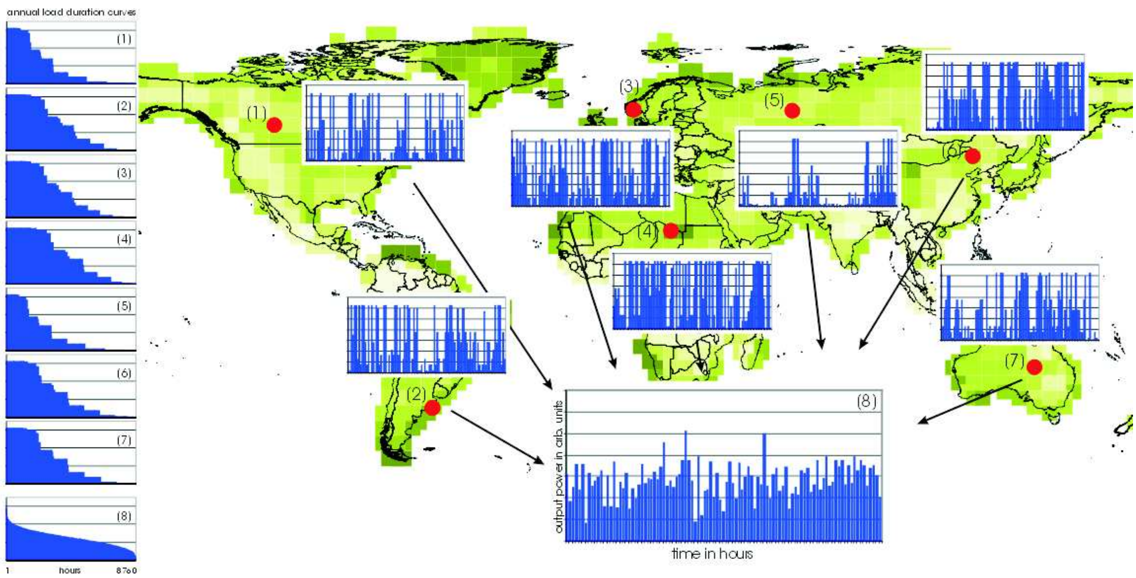


Figure 5.23: *Combined distributed energy harvest for wind power over much of the world in a time scope of 100 hours. Actual fluctuations will tend to be smoothed to an average curve for the globally connected case. Especially in view of the load duration curves for the complete year this can be easily understood (right hand side).*

patterns. Especially the consideration of the corresponding load duration curves support this outcome. The are defined as the sorted load values over a restricted time range. In the merged case this load duration curves show a more or less balanced behaviour.

Hence there are a number of reasons that do provide support for efforts to establish a global electricity grid . The *Global Energy Network Institute* (GENI) organisation is devoted to this end [GENI, 2004]. In some respects, the world is quite close to a global linkage, when all the existing long haul transmission lines are considered. Given that view, it is reasonable to devote some effort in global models dealing with this very question. To this end, the VLEEM project approach has been enlarged to cater for a global scale.
In VLEEM, particular emphasis is placed on the role that renewables can play in such a context. To this end, the world is divided in ten regions as outlined in figure 5.24. And the demand modelling component from the IIASA WEC studies (see [Nakićenović, 1998]) serve as basis for the demand.
This breakdown is a common one for global modelling and each region is represented by one or two nodes linked to neighbouring regions. The investigation in this special case is restricted to electricity. Furthermore, only solar power, wind power, and an additional back-stop technology is considered, augmented by storage technologies.

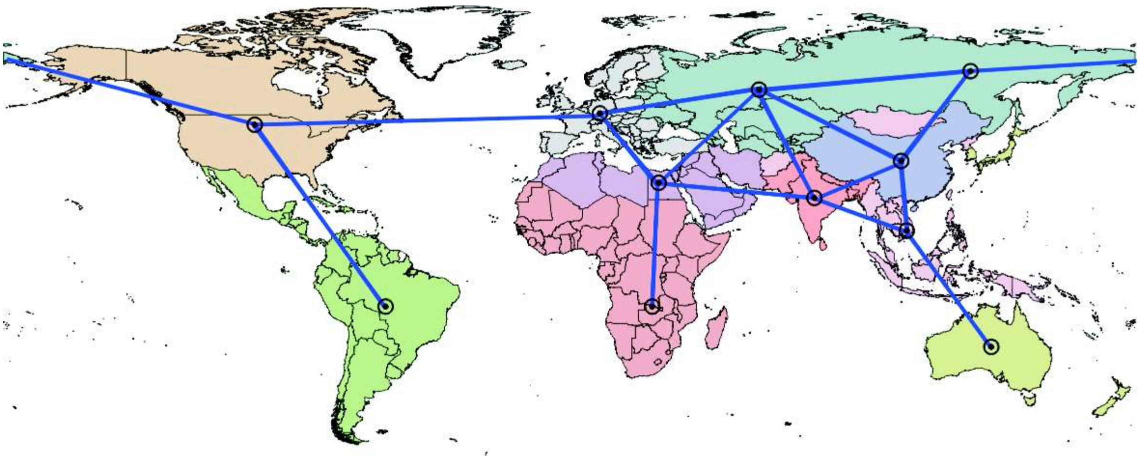
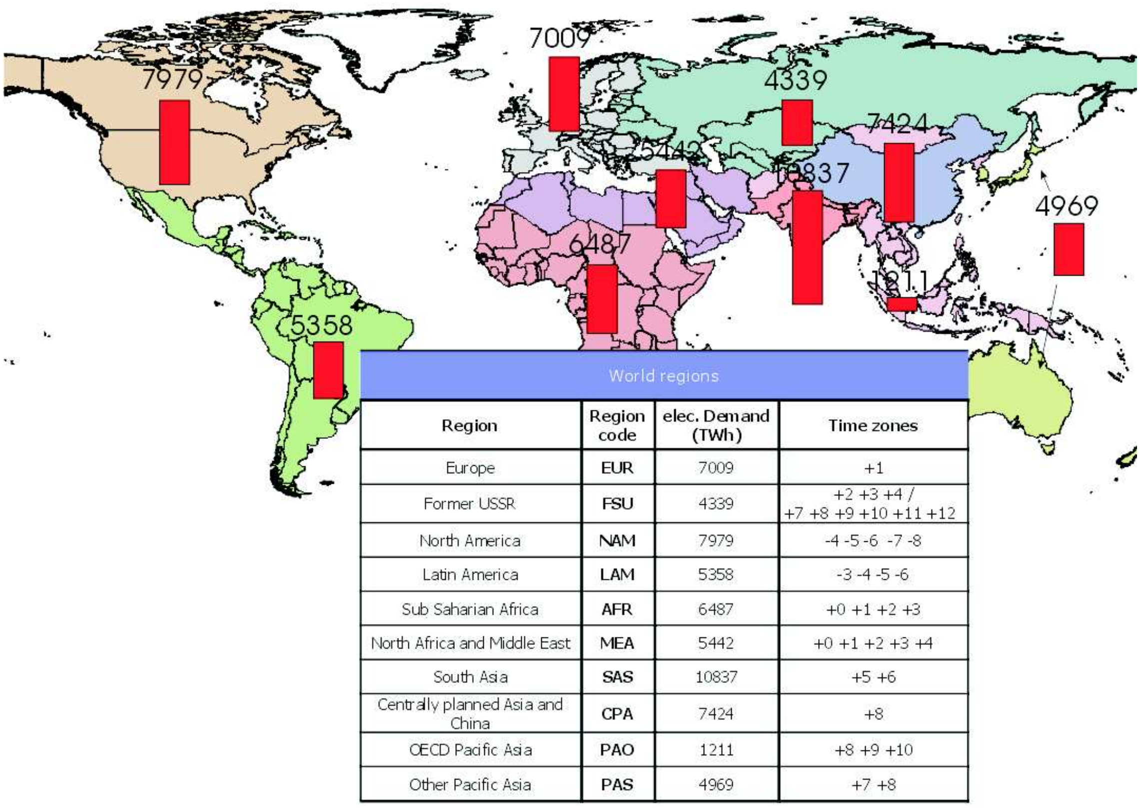


Figure 5.24: *Distribution of the world in ten regions. Each region is represented by one (or two) node(s) which are connected by transmission lines carrying electricity.*

This scenario set will be modelled over one complete year in future with an hourly time resolution. The modelling will be by linear optimisation.

5.3.3.1 Preparation of required data sets

Due to the time resolution, a method to preprocess the demand pattern is required. The demand estimates are taken from the aforementioned IIASA WEC studies. The prediction for the year 2100, by region, and restricted to electricity is depicted in figure 5.25.
The values shown in figure 5.25 are cumulative for a complete year but the model approach needs hourly values. The resultant demand load curves (see section 5.3.1) from the UCTE Statistical Yearbook 2000 [UCTE, 2001] are utilised. Merging of this information delivers a rough estimation of the periodical load behaviour in the future. Normalising these curves and shifting them from Middle European Time (MET) (-0100) to Greenwich Mean Time (GMT) now provides the base demand pattern for every modelled region.
To get a representative load curve for each region the relevant time zones are elected (see table in figure 5.25).
To gain a region-specific demand load curve, the normalised base curve is shifted by the relative values in table 5.25 and these time displaced curves will be then merged for each region. In addition, the demand patterns situated in southern hemisphere are shifted by an additional number of 4380 hours (half of one complete year). This is due to the seasonal shift.
Of course, this procedure will not fit the real demand pattern in 2100, but it will serve the purpose, that is to get a rough estimate of future electricity demand dis-



Region	Region code	elec. Demand (TWh)	Time zones
Europe	EUR	7009	+1
Former USSR	FSU	4339	+2 +3 +4 / +7 +8 +9 +10 +11 +12
North America	NAM	7979	-4 -5 -6 -7 -8
Latin America	LAM	5358	-3 -4 -5 -6
Sub Saharian Africa	AFR	6487	+0 +1 +2 +3
North Africa and Middle East	MEA	5442	+0 +1 +2 +3 +4
South Asia	SAS	10837	+5 +6
Centrally planned Asia and China	CPA	7424	+8
OECD Pacific Asia	PAO	1211	+8 +9 +10
Other Pacific Asia	PAS	4969	+7 +8

Figure 5.25: *Predicted electricity demand for the year 2100 by region, based on the IIASA WEC studies* [Nakićenović, 1998]. *The inset table also gives the time zones covered by the various regions relative to GMT.*

Scenario assumptions			
Process	**Activity Cost**	**Installation Cost**	**Efficiency**
Solar PV	-	EUR 300.00 / m^2 → EUR 2.2e–3 /m^2 /h	25%
Wind (1.25 MW turbine)	-	EUR 2.2e+6 → EUR 1.63e+1 /h	100%
Storage	-	EUR 140.00 to 14.00 /kWh → EUR 1.0e–3 to 1.0e–4 /kWh	81% (charge/discharge)
Transmission line	EUR 1.0e-11 (dummy to avoid degeneration)	EUR 0.264 /kW /km → EUR 1.9e–6 /kW /km /h	99.997% /km

Table 5.4: *Modelling assumptions used in the global electricity grid scenario. The values are used to elaborate the facilities present in a high renewables scenario.*

tributions, one which permits modelling with a high temporal resolution.

In addition to these time series which found input into the GLOBAL LINK scenario the model assumptions in table 5.4 are used again. Activity costs are expressed per hour. Cost details for PV and for wind are based on [Lako, 1998]. The last two rows in the table contains assumptions relating to storage facilities and transmission lines. The interaction between storage and transmission lie at the core of this scenario set. The cost values given for these two technologies are oriented on estimates in [VDI, 1994] and [Amos, 1998]. The resulting model behaviour in terms of storage versus transmission is of particular interest.

5.3.3.2 Optimisation results

In regard to solar and wind power opportunities, not only is an average pattern for each region required, but also the complete geographical resolution listed in section 5.3.1. Each node is considered to have a single load behaviour and a geographic position. To combine this with the consumption load pattern, each wind or solar site is associated with its nearest region representation point.

In addition to the load behaviour of each interconnecting transmission lines, an additional result for the use of linear optimisation will be the optimal capacity for each single solar or wind location. Therefore, the following limitations are added. First, only 0.5 % of the available global surface can be utilised to harvest solar energy through PV. And second, wind power is restricted to 1.25 GW per 10.0e+03 km^2. To simplify the optimisation process, an informed pre-selection of suitable solar and wind power locations is carried out. In terms of criteria, only solar locations with an aggregated insolation of 1700 kW/m^2 and wind locations with more then 3000 full load hours are "made available" for this modelling set. In addition the modelled time steps are reduced from 8760 values (each hour a year) to 2184 values (only every fourth week a year is regarded). This represents a good compromise between lose of accuracy and obtained modelling performance.

Purpose of this particular scenario set is to sketch out the geographical counteractions on a global scale, in the context of the restrictions asserted by the model definition. A spatial disaggregated preparation of the results from an optimisation series is indicated in figure 5.26.
Two scenario samples in figure 5.26 relate to two different specific storage costs (factor 10 between). One self-evident result is a common major energy flow to the projected high consuming regions of south-east Asia, China, and India. Of interest is the fact that especially Australia contributes in this scenarios, next to the utilised potentials nearby the consumption locations, to the global energy consumption cov-

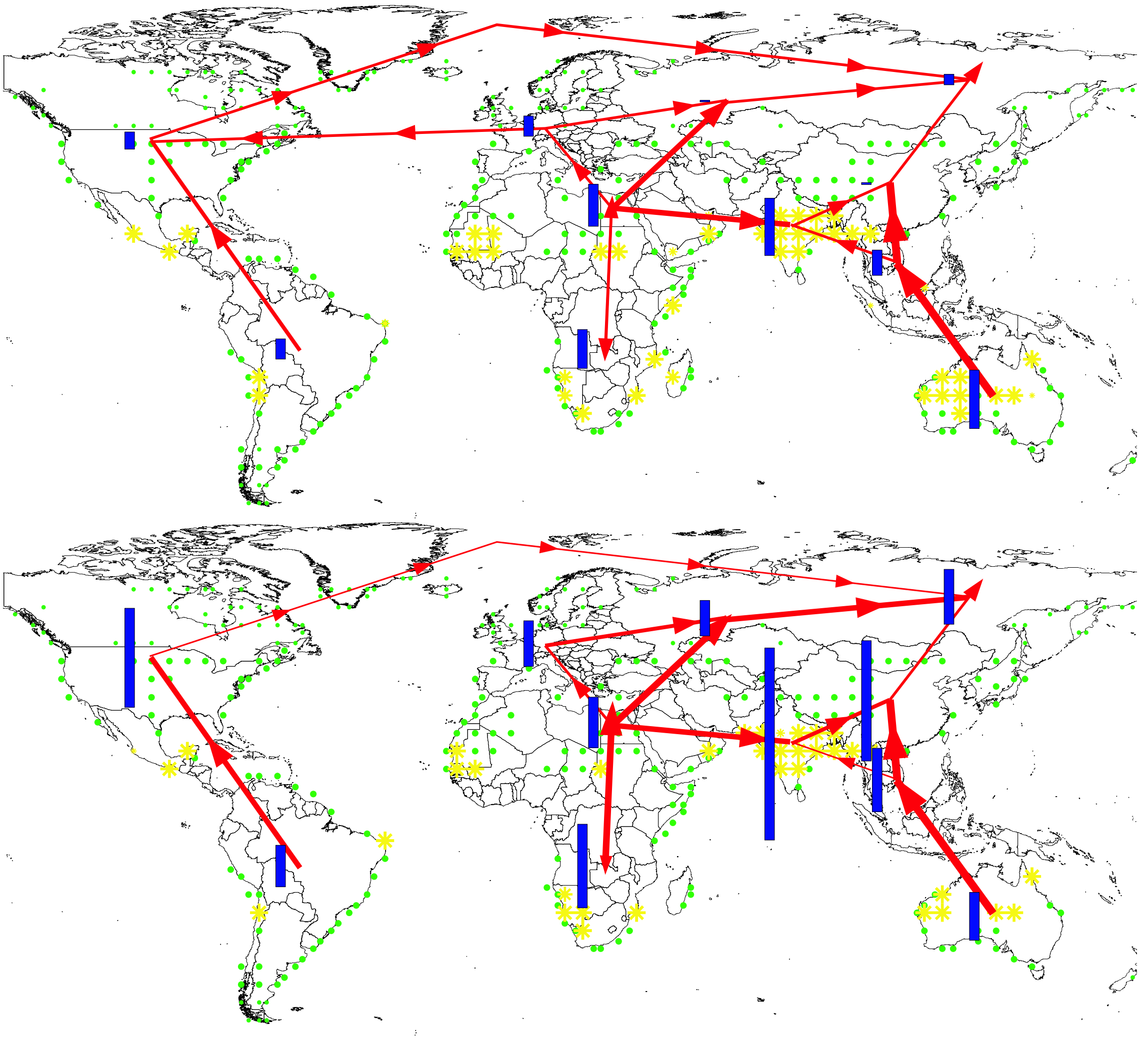


Figure 5.26: *Visualisation of the model-selected facilities by region. The storage capacities are shown as blue bars, the transmission line activities using arrow weights, solar power locations as yellow sun symbols and the selected wind energy sites as green dots of varying size. The upper scenario represents a modelling outcome with storage costs ten-fold as high as in the scenario below.*

erage. This behaviour is based on the fact that a huge potential of wind and solar energy is localised in Australia, but subject to a high fluctuation that requires huge storage to compensate. In the event of such storage being installed, the widely distributed energy sources spanning several time zones in west and south will become competitive due to the improved intertemporal match provided for by combination.

When subject to global optimisation the presented modelling results in figure 5.26 are competitive in relation to the selected constraints. One noticeable feature of the two scenarios realised, is that the installed storage increases by more than ten-fold when such storage is "made" cheaper by a factor of two or so (figure 5.30). This kind of effect is often found in networked systems. In the case here, this effect can be attributed to the changing role of storage. In the more expense scenario, storage is used primarily to buffer daily fluctuations. But in the less expensive scenario, storage also enables seasonal compensation and thereby enables a big jump in renewable energy capacity. This is because solar and wind power facilities can now potentially address a greater segment of the demand-side. More specifically, solar power exhibits strong seasonal dependencies, and so is more competitive when combined with increased storage. And wind power also better matches with respect to its high short-time fluctuations, even though its seasonal correlation is more limited than solar. These dynamics also benefit from increased transmission line capacities, which, as it happens, typically exhibit better utilisation ratios.

In most situations, no one technology can introduce major system benefits alone. Rather, it is the interplay of new opportunities in the context of the remaining system and through well managed integration that enables latent system benefits to be uncovered. In the case just presented, this required a portfolio of diverse technologies including storage and transport and a procedure for identifying optimal upgrade responses.

In addition to this scenario set a new thought was added: *What happens if no storage facilities are available?* The reason for this response is not to generate a plausible scenario but to understand the role of storage in highly renewable futures. Figure 5.27 shows the results in the case where storage is excluded.
The most obvious difference with regard to the two earlier scenarios (with storage facilities by different storage cost assumptions) and this, is that the locations for solar power change and the magnitude of installation itself increases markedly. The explanation arise from the fact that in the case of available storage, it is more competitive to produce the required energy nearby its point of consumption and use storage to buffer any temporal mismatch between production and consumption. Transmission lines are then mainly used to compensate for geographical discrepancies in demand and supply. Compared to the case without energy storage, energy

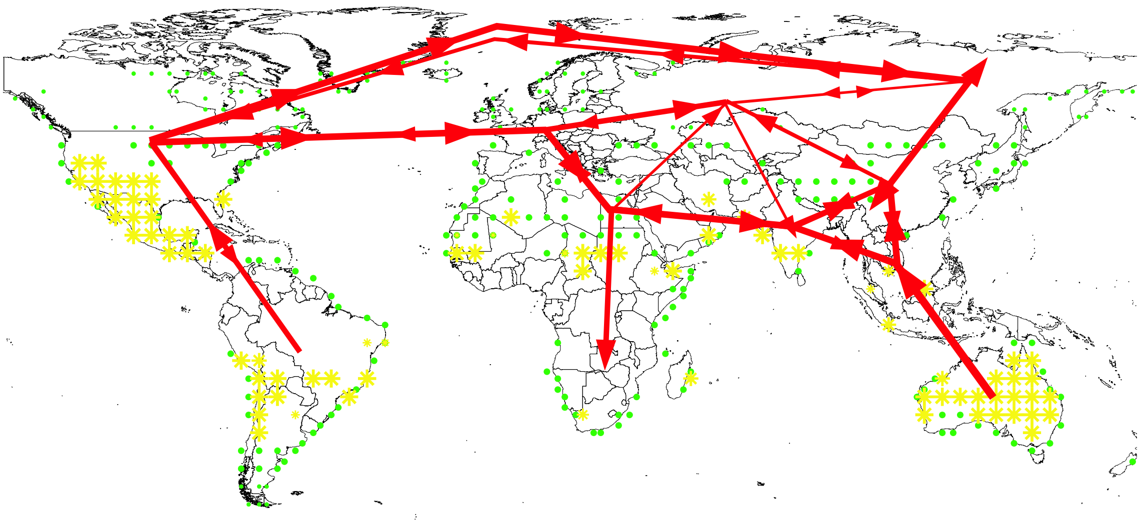


Figure 5.27: *Results from a scenario without storage. The transmission line activities using arrow weights, solar power locations as yellow sun symbols and the selected wind energy sites as green dots of varying size.*

supply must be "just-in-time" with regard to consumption patterns. This forces the system to route energy supplies from distant locations to cover the actual consumption. One clear shortcoming of this strategy is that temporal fluctuations in regional consumption or in supply facilities have a far reaching impact on the grid structure. This is evident in the fact that the grid becomes massively "oversized".

In order to obtain a better understanding of these interactions, it may be useful to consider the resulting load curves. Therefore the node located in India has been chosen for closer examination (see figure 5.28).
It is clear that, for the Indian node, the competitively selected installation of transmission lines with its two neighbouring nodes rise markedly in the case where storage has been arbitrarily excluded. In addition, the average transmission of energy also increases, not surprisingly. This can be recognised by the fact that in this particular case, a lot of energy passes through the Indian node en-route from PAS to MEA.

In the case that wind installation constraints are enlarged to 5 GW per 10.0e+03 km^2 the picture changes completely (see figure 5.29). The complete system is now dominated by wind power. A further outcome is the fact that wind power installations fit better in a global connected grid than in a peak load compensation by storage facilities. This can be understood if time deviation ranges between demand pattern and wind supply are considered. The global wind speed shows not as much sea-

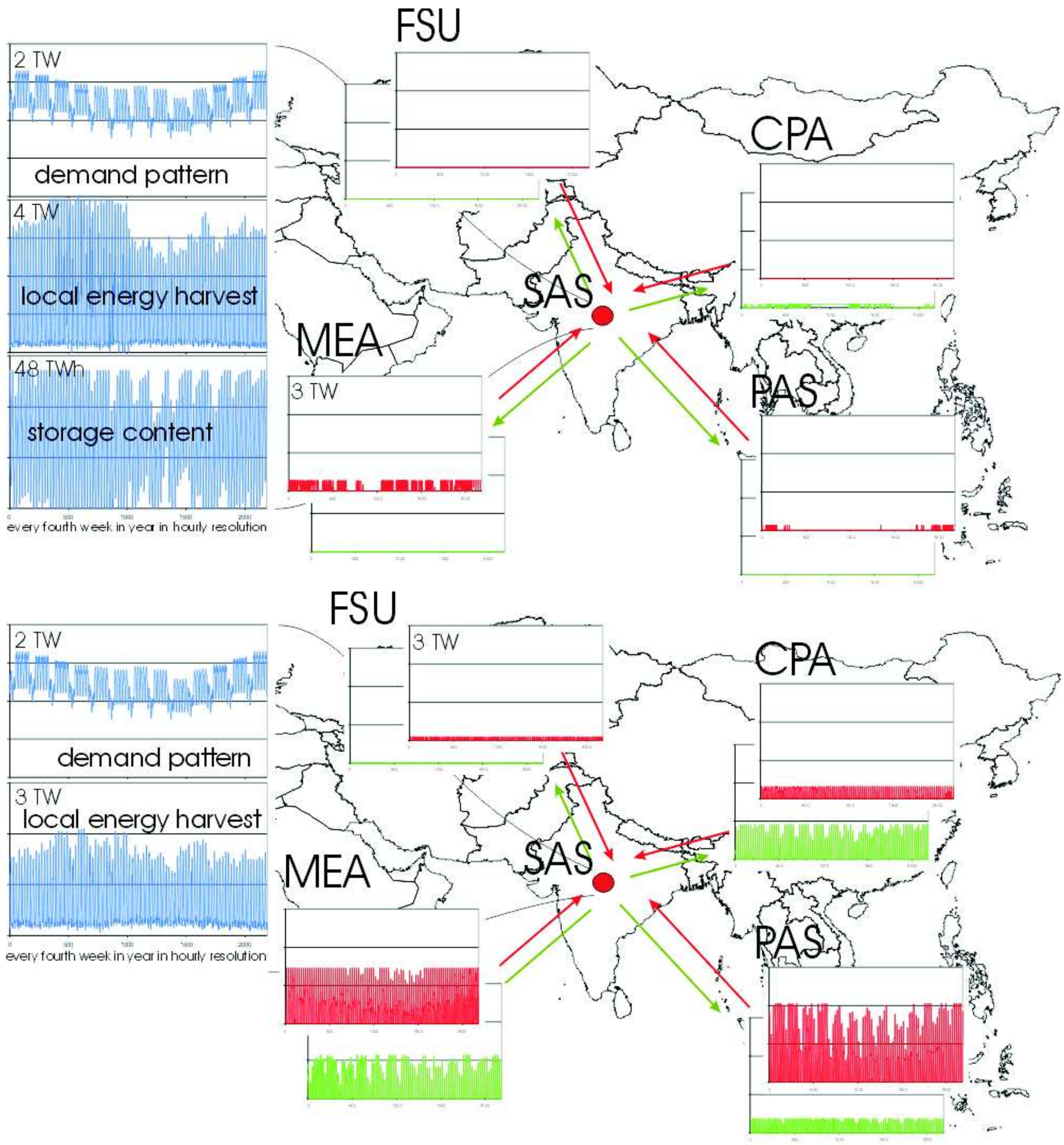


Figure 5.28: *Load curves resulting from an optimisation run for the node representing India. The first example (above) shows the load behaviour where energy storage facilities are present and the second example (below) shows the case where energy storage facilities are arbitrarily excluded. The region abbreviations are depicted in figure 5.25.*

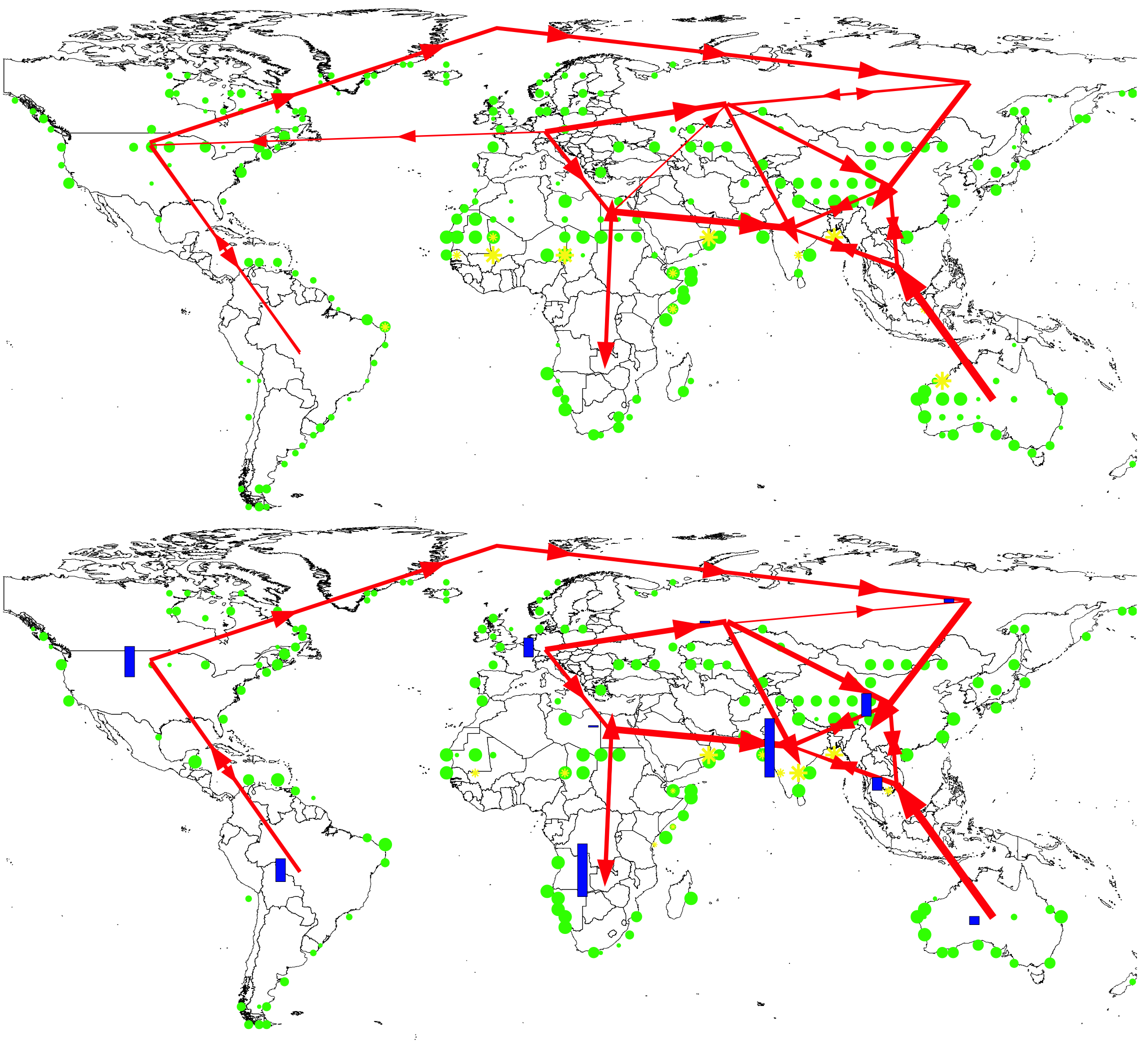


Figure 5.29: *Visualisation of the model-selected facilities by region in case of an enlarged wind power limitation. The storage capacities are shown as blue bars, the transmission line activities using arrow weights, solar power locations as yellow sun symbols and the selected wind energy sites as green dots of varying size. The upper scenario represents a modelling outcome without storage facilities while in the scenario below storage facilities were present.*

sonal dependencies as solar insolation and therefore it is, especially in the case of a merging global grid, closer to the time depending electricity demand.

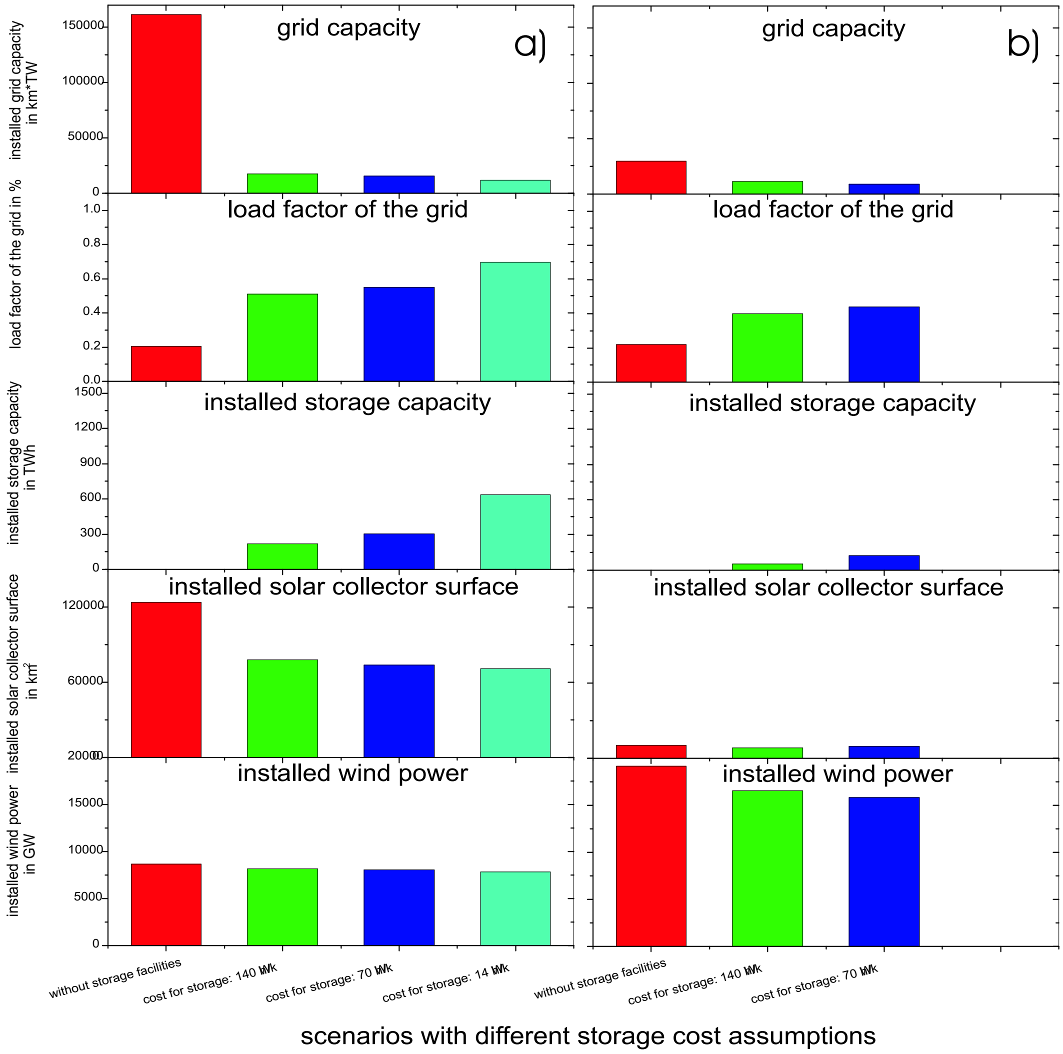


Figure 5.30: *Comparison of installations according to the contemplated scenarios with and without storage abilities. Wind power installations are limited to 1.25 GW per 10.0e+03 km^2 (a) and 5 GW per 10.0e+03 km^2 (b).*

The comparison of installations between the with/without storage scenario sets due to the reference costs given in table 5.4 is outlined in figure 5.30.

Figure 5.30 (a) shows the above mentioned “explosion” of the grid by a factor of six in the case where storage is prevented, while the average workload decreases. Also self-evident is that the competitive selected wind power installations are more

or less independent of storage abilities. This resides, as mentioned, in the fact that more short-time fluctuations than seasonal dependencies arise from wind power, but these traits are mostly compensated for by the global surrounding grid. An altogether different consequence arises for solar power. The dependency of solar power on storage must be now compensated for by more and better distributed installed capacities, as arises in the results.
In the case of enlarged wind power installation limits (figure 5.30 (b)) the impact of available storage facilities is decreased rapidly. This can be understood by the aforementioned different seasonal and time shift impacts.

The Buckminster Fuller-based scenarios provide some initial thoughts on how end-point systems might be conceived in VLEEM. And, furthermore, how the requirements of back-cast modelling might fit with the capabilities of TASES. In particular, the role of geographically and temporally disaggregated modelling techniques in relation to the projected supply opportunities and consumption patterns. The examples provided allow a quantitative investigation of the interactions which arise in the chosen scenarios. The scenario definitions are strongly influenced by the quality and conception of the underlying mapped system database. Even in light of the simple assumptions regarding consumption patterns in the scenarios presented here, the interpretation of scenario results requires an astute understanding of networks.

Finally, the scenarios and analyses provided in this thesis should be understood as proof-of-concept exercises and not as fully developed assessments. Sophisticated evaluation will require both a greater attention to detail and a more careful selection and defence of the scenarios themselves.

Appendix A

Description and user notes for TASES

TASES (**T**ime **A**nd **S**pace resolved **E**nergy **S**imulation) is a software environment for modelling and optimising future energy system scenarios. TASES can be used in various modes, including back-cast modelling. TASES is well suited to problems with significant amounts of renewable sourcing and/or energy storage. TASES is joined to a graphical user interface and an extensive database (see figure A.1).

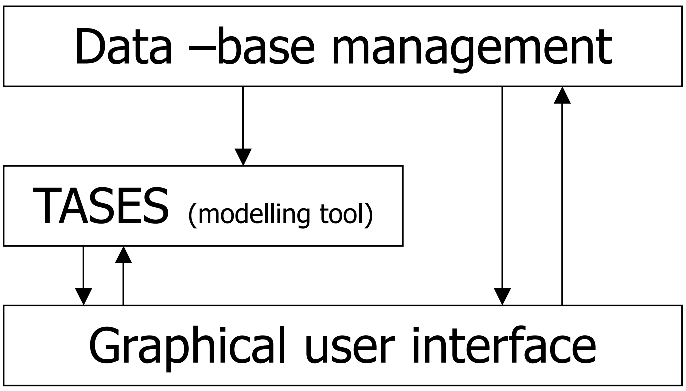


Figure A.1: *The software components which make up* TASES.

TASES is used to map real or envisaged energy systems at any selected space and time resolution. It was completely developed, including the graphical user interface in ArcView, within the framework of this thesis. The body of this thesis provides most of the theoretical background to TASES.

A.1 Use of TASES

TASES itself comprises several more or less independent modules (software components). TASES is built around a base module which provides a flexible way to represent all kinds of entities found in real energy system: energy flows, material flows, transformation processes, storage facilities, and so on. These entities are mapped to an arbitrary time and space scale data structure (as explained in section 2.3.1).

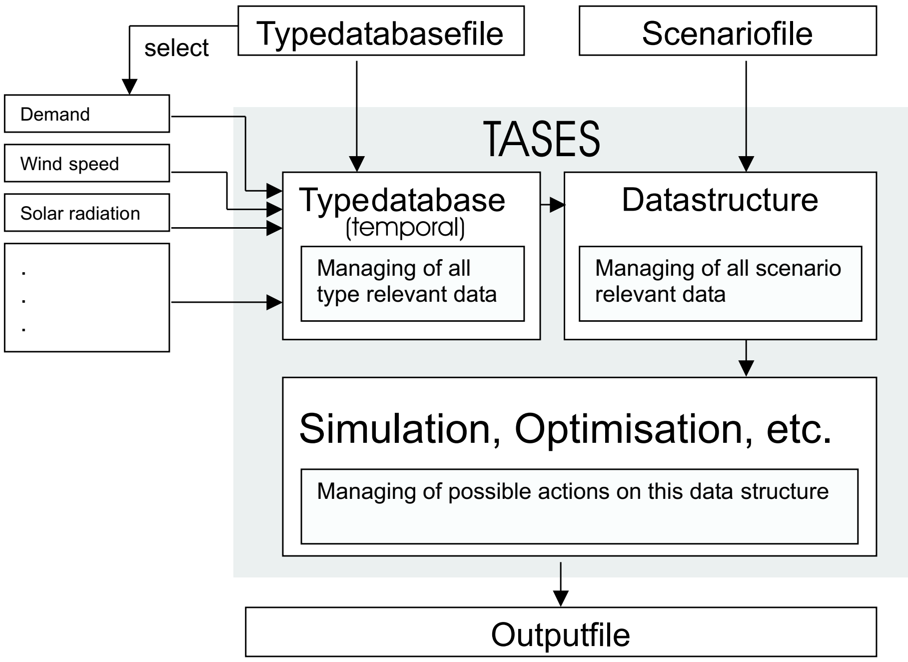


Figure A.2: *Internal data flows with the data input and output interfaces shown.* TASES *itself is represented by the shadowed rectangle.*

The interface to external data bases and the internal module structure is sketched in figure A.2. The following three module families can be distinguished: TYPEDATABASE, DATASTRUCTURE, SIMULATION or OPTIMISATION.

A given scenario is populated with interconnected processes and facilities. The method for generating and connecting these individual entities can be interpreted as follows:

- first, programmers hardcode prototype entities into TASES for use in future models,
- second, users define generic entities, by means of these hardcoded prototypes,

- third, users populate their scenario by instating their generic entities, and
- fourth, users configure their scenario by specifying entity connectivities.

The first point is embedded in TASES. The second point utilizes the *typesdata* and associated files. And the third and fourth points utilize the *scenario* file.

The TYPEDATABASE module is responsible for the dynamic administration of all mathematical quantities related to an individual process during a modelling run and is implemented as a database. Similarly, the DATASTRUCTURE module manages all the scenario relevant data. These two modules manage the model run and applicable modelling actions throughout a scenario are performed in corresponding modules such as SIMULATION or OPTIMISATION.

A.1.1 Data preparation

All external data sets are organised in ordinary ASCII text files. The data relating to processes is collected in the *typesdata* file. This includes type (e.g. plant, storage), efficiencies, emissions, investment, and operational costs, and so on. The syntax of this file is determined by sections as follows:

```
*
<prototype>
<type>
<parameter_1>  <availability>  <value_1>  <value_2>
<parameter_2>  <availability>  <value_1>  <value_2>
.
.
*
```

Each section of this format determines one specific process group. An example file containing process groups is shown (in part) in figure A.3.
The start and end of a process specification is indicated by an asterisk in column one. Each process group must be assigned to one so-called *prototype* as enumerated in table A.1.
The purpose of this classification is to develop a simple hierarchical organisation for the underlying process types. The idea is that each individual process type can be assigned to variously a demand, transformation, transportation, distribution, storage, resource harvest, or mining stereotype. Note that not all of these types have been implemented as yet.
The declared prototype is followed by special type declaration (an arbitrary string) representing this process type this section addresses. Next the parameter set starts. The parameter declarations are hardwired into the software. Supported parameters are enumerated in table A.2.

Process and commodity prototypes	
Parameter	**Explanation**
DIST	stands for process types responsible for distributing commodities
DEMAND	encloses all relevant demand types
SUPPLY	encloses all conversion techniques
STORE	encloses all storage abilities
C_NET	first commodity prototype
H_NET	second commodity prototype
E_NET	third commodity prototype

Table A.1: *List of process and commodity prototypes. Processes are naturally covered by nodes.*

Describing parameters	
Parameter	**Explanation**
SEFF	Efficiency according to first commodity
WEFF	Efficiency according to second commodity
PPP	Price Per Power – investment costs
PPE	Price Per Energy – energy costs
DEM	Demand value
OCO2	CO_2– emissions per primary energy unit

Table A.2: *Hardwired parameters common to all plant.*

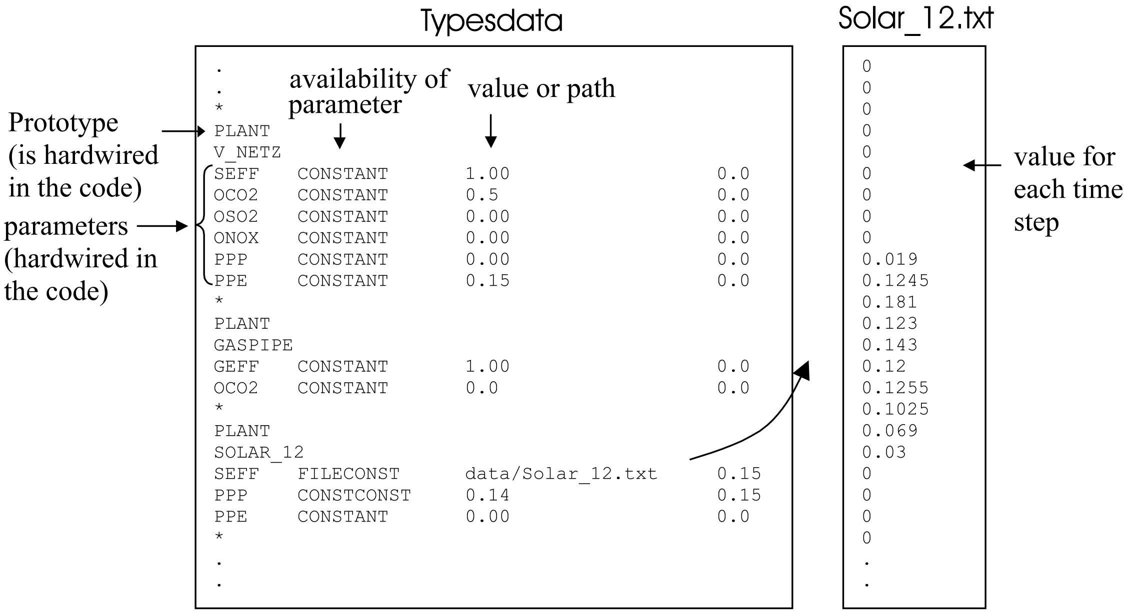


Figure A.3: *Representative data input format with the actual data stored as tab-separated ASCII text. The 'typesdata' file is depicted on the left-hand side. Each process type declaration is followed by the required parameters. The right-hand side shows an example of a parameter time series, duly referenced from the 'typesdata' file.*

The parameter set provides specific values for a process type. Specific values, in this context, indicates quantities that are specified in per unit terms. Specific values can be single constants, valid for the complete modelled time horizon. Or they can be provided as time-series providing values for each individual time step. The type of parameter is indicated in the <`availability`> field by the strings enumerated in table A.3.
So far, two ways of representing parameters have been described: a fixed value or a complete column-oriented time-series. A third option is also supported and is used to rescale an existing time-series by a constant multiplier. This ability, for instance, facilitates the implementation of solar power. In this case, radiation patterns can be served by complete data series while the conversion efficiency is assigned by a fixed efficiency, valid for the complete time horizon.

In the third and fourth fields, the parameter value is represented according to the declared availability. In the case of a constant parameter the third field contains the value and the fourth is neglected. If the parameter is represented by a column-oriented time-series, the third field contains the path to an external ASCII–file (see figure A.3, left-hand side) and the fourth field is neglected. In the case of the rescaled

Access to parameter	
String	**Explanation**
CONSTANT	parameter is available as fixed floating value valid for the complete time horizon
FILE	parameter value is provided as data row in an external file representing each single time step
FILECONST	parameter value is provided as data row in an external file which will be multiplied with a fixed floating value valid for the complete time horizon

Table A.3: *Designating strings to indicate parameter availability.*

time-series, the fourth field contains the value of the rescaling factor.

The *scenario* file describes an individual model scenario, especially the topology (that is, connectivity) of this scenario. Scenario names are not fixed by TASES, but can be freely chosen by the user. This file is, as before, separated in sections and uses the following syntax:

```
*
CREATE
NODE            <process_type>
TYPE            <type>
NAME            <name>
<parameter_1>   <value>
<parameter_3>   <value>
.
.
*
.
.
*
SETCON
<parameter>     <value>
*
.
.
```

An example *scenario* file, using this syntax, is shown in figure A.4. The *scenario* file contains all the individual processes that go to make up the complete system.
Each entity definition is indicated by an asterisk in column one at the beginning and at the end of the enclosed section. The first line in this section indicates, via one of the two keywords `CREATE` or `SETCON`, as to whether this section is used to instantiate an individual entity or simply to set an global scenario parameter.

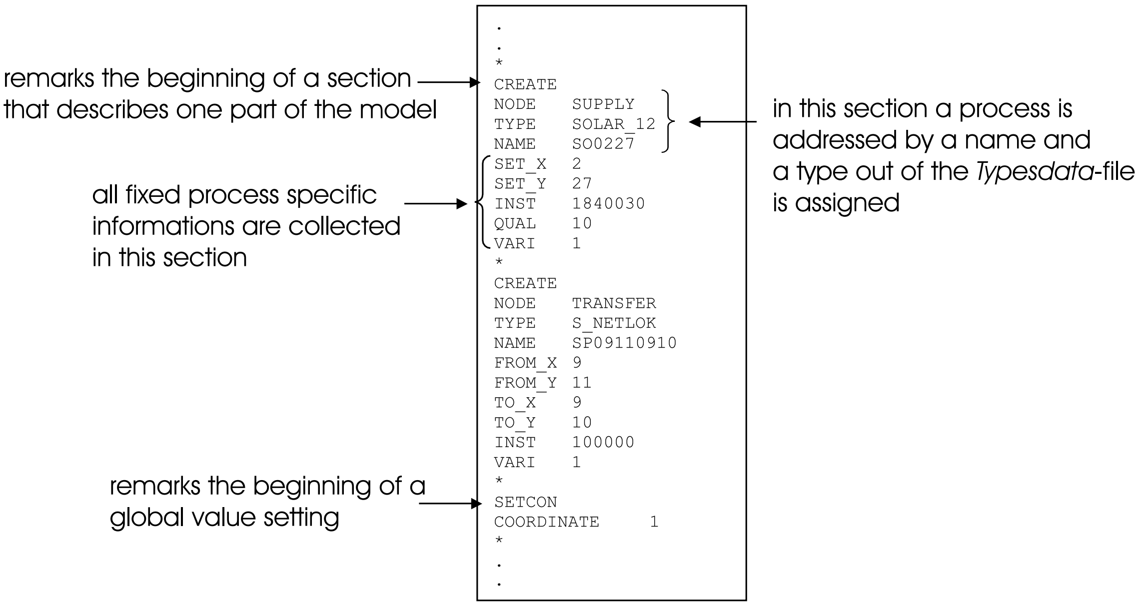


Figure A.4: *Syntax of the 'scenario' file. All entities participating in a particular scenario are referenced and all for the limitation of the scenario responsible parameters are collected.*

Parsing (reading) of the *scenario* file catches in general all central contents of the model run whereas the sum of the `CREATE` sections encapsulates all of the entities within a modelled scenario.
In the case of a `CREATE` section, the `process_type` statement determines the process type of the particular entity. The supported process types are depicted in table A.4. The next line in the *scenario* file indicates a predefined `type`, fixed by a string, that is also given in the *typesdata* file. The third line provides that process with an unique `name` (relative to that type).

The next part of such an entity defining section is not hardwired and contains all process attributes unique to this instance of the describing values, joined to this individual entity. The first field contains the string representing the parameter and the second field contains its value.
Thereby the first segment is devoted to the spatial location of the process in question and to any further parameters assigned to this entity that had not been defined by the assigned process type, defined in the *typesdata* file. These new parameters relate to instance-specific information like installed capacity and not to process-specific information like conversion efficiency.
Supported parameter strings are enumerated in table A.5.
So, all in all, entity defining sections (enclosed by two asterisks) define an individual

Available process types	
String	**Explanation**
SUPPLY	conversion process
DEMAND	demand process
STORE	storage process
DIST	distribution process
TRANSFER	linkage process

Table A.4: *Supported process types, as used in the scenario descriptions contained in the 'scenario' file.*

Process defining individual parameters	
String	**Explanation**
SET_X	x value of location coordinate of location fixed process
SET_Y	y value of location coordinate of location fixed process
FROM_X	x value of starting location coordinate of a transportation process
FROM_Y	y value of starting location coordinate of a transportation process
TO_X	x value of ending location coordinate of a transportation process
TO_Y	y value of ending location coordinate of a transportation process
INST	installed capacity for this process
INST_B	installed blocks (block size is defined in Typesdata) – if installation is quantised (only if no INST is defined)
QUAL	quality value designated to this process
AGE	actual age of a process according to the starting point of modelling
BILANZ	indicates weither a distribution process acts as balance ore not (1 or 0) – its only for internal modelling algorithms
VARI	indicates weither installed capacity of an process can be changed (1 or 0) during optimisation tasks
LOAD	starting load value for a storage process during

Table A.5: *Individual process defining parameter set.*

Scenario relevant parameters	
String	**Explanation**
COORDINATE	indicates how positioning values should be interpreted – spherical or cartesian (1 or 0)
UNIT	offers the transformation value for output data regarding to input data
MINQUALSTORE	contains a minimum bound for considered energy paths to stores (in simulation purposes only)
MINQUALREST	contains a minimum bound for all other energy paths to demand structures (in simulation purposes only)
TOFFSET	regarding to the position in offered data rows for parameters, the value indicates the starting time step for modelling
MAXPOLL	in optimisation purposes an maximal emission value can be set
TIME	number of time steps to be modelled

Table A.6: *Supported parameters related to the scenario at large, as opposed to single processes. Some of these parameters are technical in nature while others can be used to define model-wide limits when developing scenarios.*

process in combination with data residing in the assigned process type specification the assigned and contained in the *Typesdata* file.

Returning to the second section option located in the *scenario* file, prefaced by SETCON. Sections of this form contains one of the supported model-wide parameter settings enumerated in table A.6. The SETCON section is used to set boundary values not related to a single process but applying to the entire scenario. Parameters include the selected time resolution, scientific unit conversions in use, upper-bounds on aggregate emissions, and other preset global limits related to a simulation or optimisation purpose relevant to the investigation at hand.
The combination of these two files, the *typesdata* file and the *scenario* file contain all the information required to model a scenario using TASES.

A.1.2 Running TASES

TASES itself is command line oriented and can be invoked using the syntax outlined in figure A.5.
As mentioned in section 2.3.1, the software package consists of hierarchically ordered modules. The fundamental module, known as DATASTRUCTURE, is responsible for data management and for overall control.
The different interfaces to the simulation or optimisation modules are activated via

indicates what modul will be applied

name of the scenario file

name of the output file which collects all results

```
c:/TASES/tases SIM ucte_base ucte_result
```

Figure A.5: *Representative command line syntax for* TASES.

Execution flags	
String	**Explanation**
`SIM`	The operation mode of a model will be simulated.
`OPT`	A model will be optimised by the implemented evolutionary algorithm.
`OSI`	The model design will be optimised by an evolutionary approach while the operation mode of the model is simulated.
`MPS`	A model will be formulated in a MPS-matrix which can be solved by linear solvers.
`COL`	Only input data sets will be served in an aggregated form.

Table A.7: *User-specified flags which control the run-time behaviour of* TASES.

a flag, as indicated in table A.7. It should be noted that, in the case of linear optimisation, TASES generates a MPS formatted matrix which is then passed to third-party software for solution.

The *scenario* file describing the model and the *output* file in which modelling results are to be collected, are also given as command line parameters, in the order indicated.

Following a run, the results are collected in the nominated *output* file using ASCII text. This file contains a sequential listing of all processes present in the modelled scenario, each with its assigned load curves. The *output* file uses the following structure:

```
<objective_value>
<installation_process_1>     <value>
<load_process_1_timestep_1>  <value>
.
.
<load_process_1_timestep_n>  <value>
<installation_process_2>     <value>
<load_process_2_timestep_1>  <value>
.
.
<load_process_2_timestep_n>  <value>
.
.
.
```

An example of this output syntax is given in figure A.6.

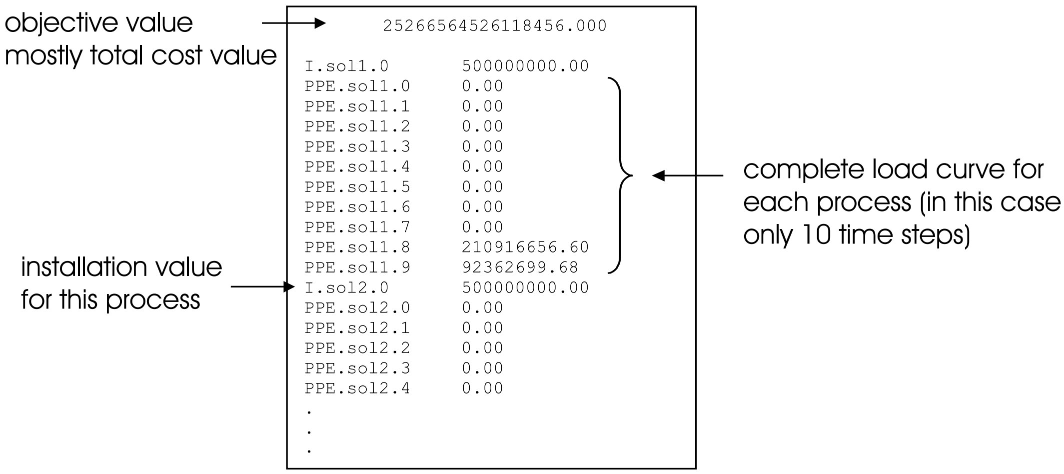


Figure A.6: *Illustrative output from the output file. This file contains the entire primary results dataset.*

In the case of scenarios with hourly data spanning a complete year, an *output* file can run to a few hundred megabytes. Pertinent results were extracted using command line tools like grep, for use in subsequent analysis and visualisation.

A.2 Graphical interface for TASES

The large amount of data to be handled, arising from both input and output, made it difficult to maintain an overview using text file-based data management. A more sophisticated approach was indicated and the ArcView package from Environmental Systems Research Institute, Inc. (ESRI) was selected for the task. ArcView is one of the industry leaders for geographically referenced data management. ArcView can transform and display such data on any common map-base and also provides spreadsheet-like features to aid data entry and exchange. In addition, ArcView has its own macro language to facilitate the creation of user dialogs and processing scripts. For these reasons, ArcView made a sensible choice for the development of a user-oriented front end for TASES.

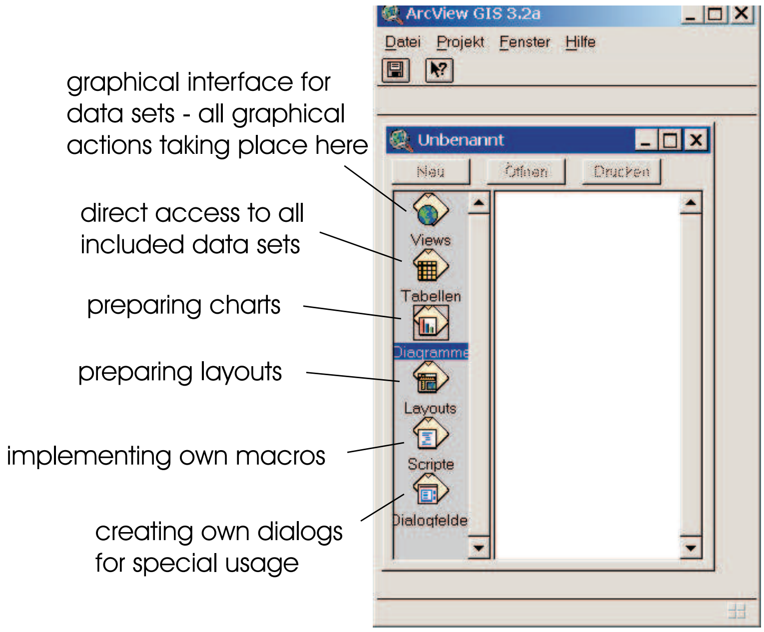


Figure A.7: *An annotated screen-shot indicating the features provided by ArcView.*

The appearance of ArcView is shown in figure A.7. For each project in ArcView, the functionality indicated is available. Most forms of spatially referenced data can be read in (the *Tabellen* (tables) icon) and visualised (the *Views* icon). The most common interface format for external datasets is *dBASE IV*, although various ASCII text and proprietary spreadsheet formats are also supported.

With regard to TASES, the two lowest icons are the most interesting. The *Scripte* (scripts) icon allows macros to be written and run. Such macros are used to invoke TASES and to generate or read TASES input and output files, respectively. The *Dialogfelder* (dialog box) icon allows project-specific user dialogs to be developed with reduced effort.

A front-end for TASES was duly developed, based on the graphical interface and data management features of ArcView. The outcome of this work is described in the following with reference to a particular modelling project.

To emphasis the geographical nature of TASES, the ArcView *Views* feature was utilised most. This allowed the underlying spatial structure at the nominated modelling resolution to be viewed, as shown in figure A.8.
In addition, this same underlay could be used to visual model results and other pertinent datasets, including spatial population density, resource distributions, and environmental impact of various sorts.

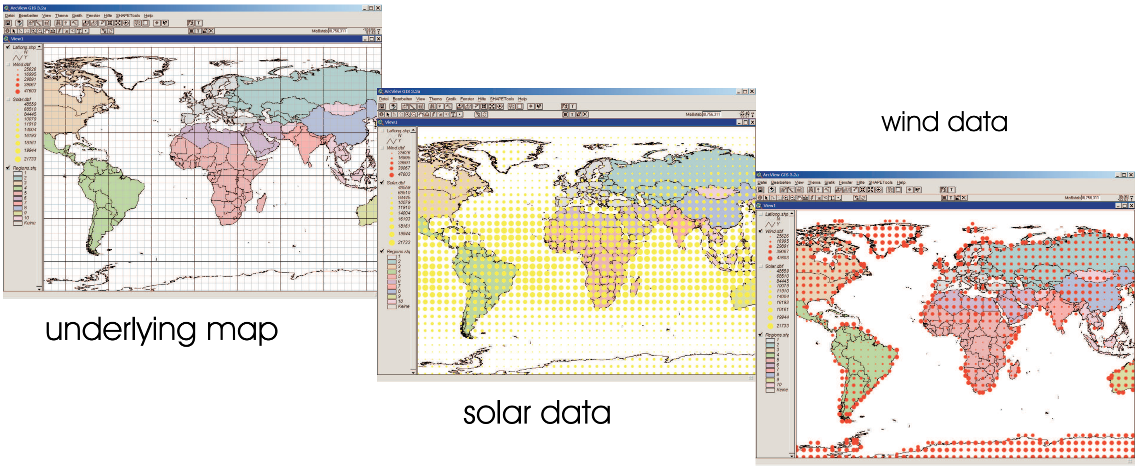


Figure A.8: *Inclusion of geographically referenced datasets, pertinent to problem at hand, to assist with scenario preparation.*

The approach indicated can be extended to enable direct access to the process types defined in the *typesdata* file and particularise these for use in location-dependent roles. The user interface for this is shown in figure A.9.
The *typesdata* dialog box enables the user to scroll through the currently supported process types and either manipulate or add new process entities to a scenario. In fact, location-referenced types can be generated directly by choosing the required type identifier and then clicking on the desired map location. This functionality uses a table containing TASES type names which must of course match those present in the *typesdata*-file.

The combination of the features just described (and others) enables the management of huge datasets in a very clear fashion. The entire database can be manipulated and extended in a convenient way through development and use of dialog boxes.
A scenario can also be created and manipulated in a graphical fashion. This requires two themes to be added to the *Views* context. The first, uses points (point shapes) for all point-oriented processes (for instance, power stations). And the second uses lines (polyline shapes) for all connect-oriented processes (for instance, power lines).

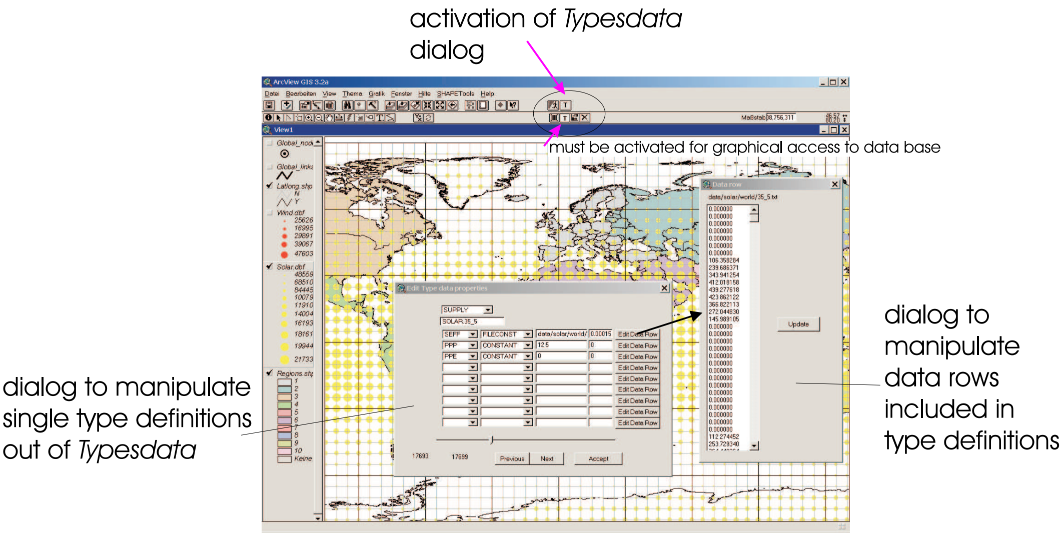


Figure A.9: *Manipulation of the 'typesdata'–file. Each defined process type can be conveniently reached by scrolling through the dialog box, as indicated.*

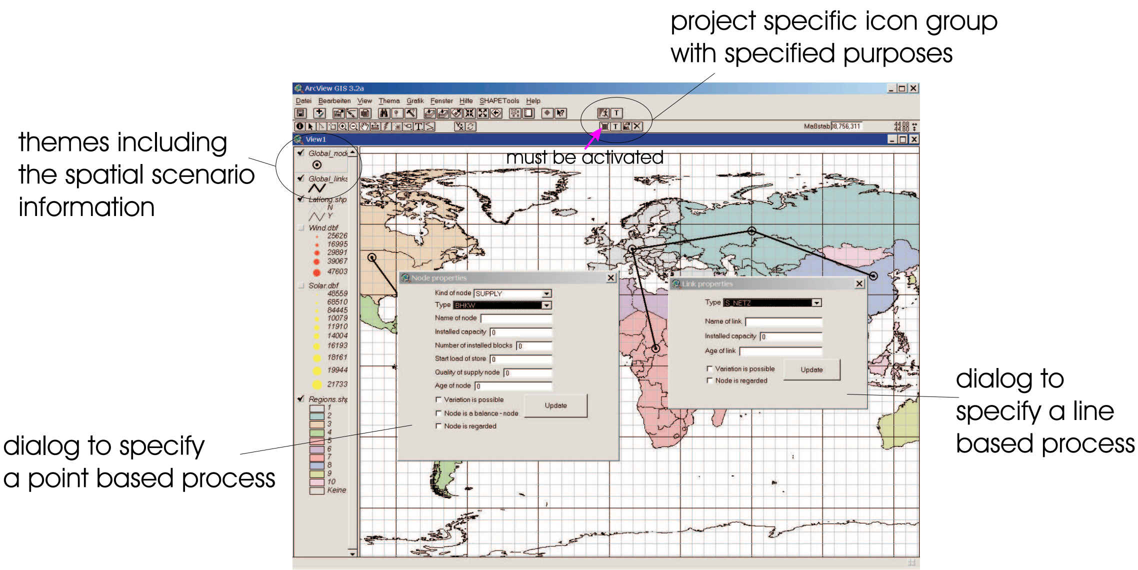


Figure A.10: *Preparation of a model. Two themes in the View-section contain all the spatial information related to a scenario and the specification of individual processes is realised via dialog boxes. The dialog box on the left-hand side is the interface for point-oriented processes and the right one for line-oriented processes.*

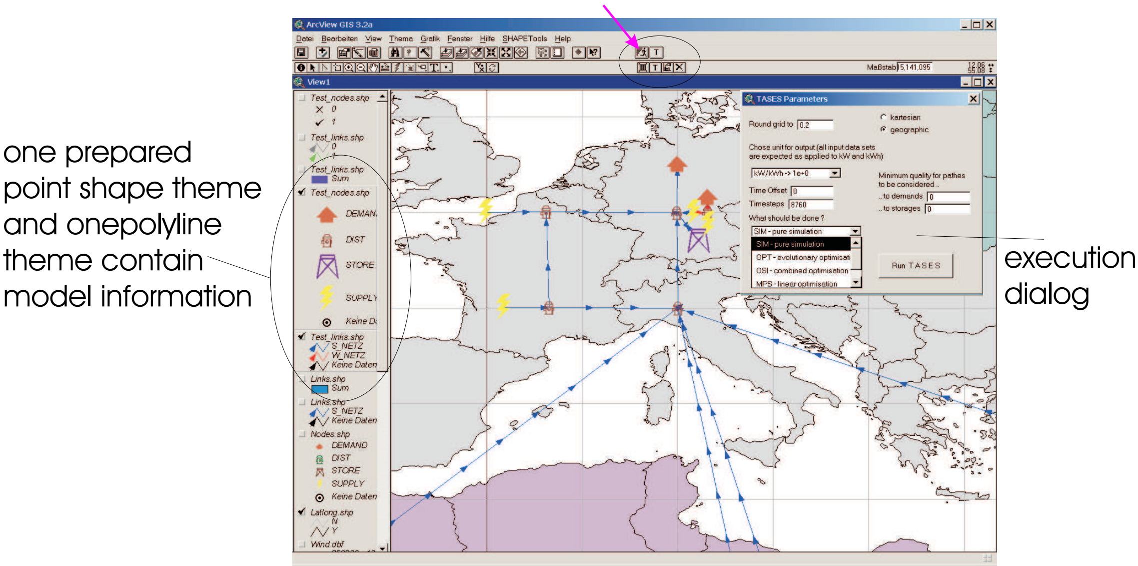


Figure A.11: *Execution dialog for a* TASES *run. The last few scenario-wide parameters can be set here, if need be.*

The locations of these processes utilise references underlying maps, accessible via the graphical interface offered by ArcView. Specific details for these processes can be entered via corresponding dialog boxes. Clicking on a process activates (assuming the correct function is selected) bring up the relevant dialog box, as shown in figure A.10.

Also useful is the accessibility of the relational tables which contain the TASES registration information. These tables are stored in `*.dbf` format files. This provides the opportunity to handle the data sets for systematic data manipulations in more suitable external applications like MICROSOFT EXCEL and ACCESS. Due to the straightforward data interfaces, the flexibility in terms of data manipulation is very high. Each process can specified via internal dialog or via external data manipulation, and, once the dataset is complete, the model can be executed.

The execution of TASES can also be run through a dialog box, implemented as part of the project. This dialog (figure A.11) manages any additional parameters needed for a proper run which were not already given in the *typesdata* or *scenario* preparation dialog boxes.

After TASES completes, its command line output is presented in a new dialog window. If this indicates success, mentioned output file is created. In a first standard evaluation, also implemented as part of this project, an additional *View* context shows the cumulated load curves for each connection process. The connection pro-

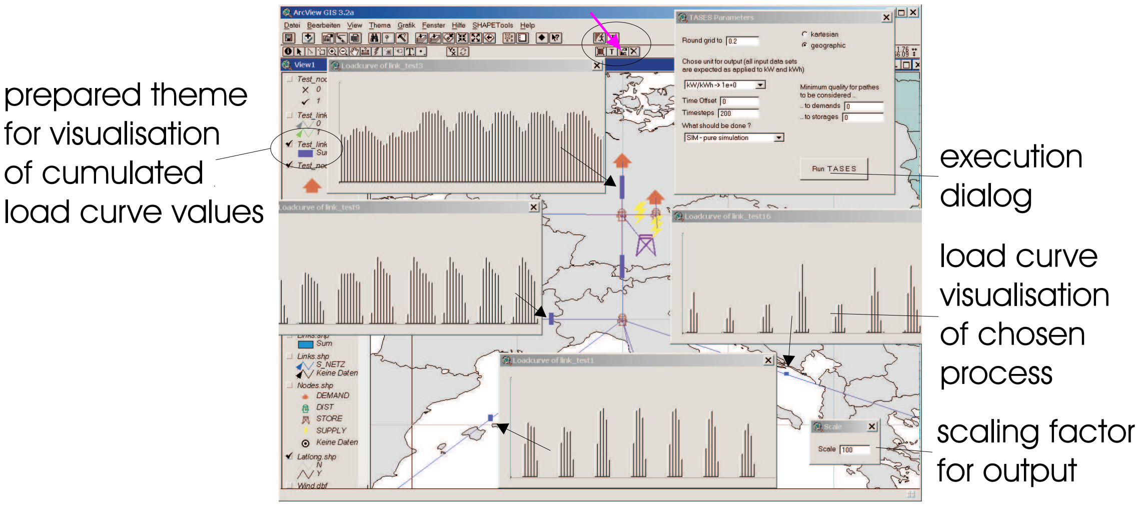


Figure A.12: *The visualisation and evaluation abilities offered within the GIS project. The connection processes can be visualised within an own View theme with its cumulated load curve and, in addition, each load curve can be completely displayed in its own dialog box.*

cesses, taken together, contain the bulk of the modelling results of interest to most users. Another evaluation option on offer is the visualisation of each load curve. In this case, the relevant icon is chosen by a click.
The aim of the graphical interface project is to provide users with fast and easy access to the features supported by TASES. The interface developed using ArcView certainly affords the user integrated management of most of the capabilities offered by TASES-style modelling. But no graphical interface can match the flexibility of manual input, specialist pre- and post data processing, and custom results processing. Therefore an exact knowledge of the input and output file formats for TASES is highly advisable. Even so, the graphical interface enables the user to gain a useful tool. And it provides an opportunity to *experiment* in the manner of *what if . . . ?*, because the effort required to change parameters and visualise results is now trivially low.

In this context, the result is a graphical front–end, provided by way of the ArcView environment, and a command line back–end to the modelling program TASES. This first experience with a graphical interface, arising from consideration of both user needs and numerical requirements, looks set to provide an excellent co-evolution.

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